DEVELOPMENT AND ACTIVITIES OF ROOTS OF CROP PLANTS

A STUDY IN CROP ECOLOGY

BY

JOHN E. WEAVER, FRANK C. JEAN, AND JOHN W. CRIST

PUBLISHED BY THE CARNEGIE INSTITUTION OF WASHINGTON
WASHINGTON, MAY, 1922

DEVELOPMENT AND ACTIVITIES OF ROOTS OF CROP PLANTS

A STUDY IN CROP ECOLOGY

BY

JOHN E. WEAVER, FRANK C. JEAN, AND JOHN W. CRIST

PUBLISHED BY THE CARNEGIE INSTITUTION OF WASHINGTON
WASHINGTON, MAY, 1922

CARNEGIE INSTITUTION OF WASHINGTON
Publication No. 316

TECHNICAL PRESS
WASHINGTON, D. C.

CONTENTS.

LIST OF ILLUSTRATIONS.

PLATES.

TEXT-FIGURES

TEXT-FIGURES—continued.

DEVELOPMENT AND ACTIVITIES OF ROOTS OF CROP PLANTS.

A STUDY IN CROP ECOLOGY.

BY

JOHN E. WEAVER,
Professor of Plant Ecology in the University of Nebraska,

FRANK C. JEAN,
Professor of Botany in the Peru (Nebraska) State Normal School,

AND

JOHN W. CRIST,
Instructor in Botany in the University of Nebraska.

DEVELOPMENT AND ACTIVITIES OF ROOTS OF CROP PLANTS.

INTRODUCTION.

Some of the most fundamental problems of plant ecology in its manifold relations to crop production are those concerned with root development and the relations of roots to soil and subsoil. An exact knowledge of the root development of crop plants, of their position, extent, and activity as absorbers of water and solutes at various stages of growth, is of paramount inportance to a scientific understanding of plant production. Moreover, a knowledge of modifications produced by variations in the subterranean environment, whether due to such natural conditions as excessive water-content or drought, or to tillage or fertilizers, is of no less importance. In fact, many processes and practices will cease to be empirical and come to be exact only when the relation of roots to soil is recognized as having fundamental value.

The importance of root extent and distribution in a study of soil-moisture is patent. These should determine not only what depth of sample should be used, but also the maximum depth to which samples should be obtained. The time, method, and amount of the application of water for irrigation studied in the light of root development furnish a rich and varied field for investigating problems of the greatest scientific and economic importance. Conversely, the proper drainage of swamps and boglands for pastures, meadows, afforestation, or for cultivated crops, should be determined with reference to root relations. (*Cf.* Howard, 1916, 1918; Osvald, 1919.)

A knowledge of root systems is again fundamental in the scientific application of fertilizers. In fact, it should furnish the criterion not only for time and amount, but also in regard to the manner and depth of such application. In securing soil samples for chemical analysis, root extent and activity at different levels should determine the depth at which the samples are taken. Moreover, it will clear up the whole problem of the relative values that should be placed upon chemical analysis of surface soil and subsoil.

Preliminary studies of root systems of native plants in soils impregnated with alkali point out clearly that the adaptation of plant to habitat is often largely one of root distribution above or below the layers of greatest salt concentration. With adequate knowledge of the variability of the root systems of different varieties of crop plants, selection of those most suitable for cultivation in such areas should be less difficult.

In problems of crop production on acid soils, if attacked from the more modern and logical viewpoint of lime requirement of the plant, rather than that of the soil, the root system again plays a decisive rôle. The lime requirement of the plant is determined not only by its lime-content and rate of growth, but especially by its feeding power for lime. The latter is in proportion to the character and extent of the root system, the internal acidity of roots,

and their excretion of carbonic acid (Truog, 1918). A knowledge of root position and extent is of prime importance in studies of aeration and the closely allied phenomenon of soil toxicity. Passageways left in the soil, after the roots have decayed, afford greatly increased possibilities for aeration.

The important problem of the relation of various methods of tillage to root development is one of which we are almost entirely ignorant. The value of various depths of plowing, listing, or subsoiling, and the preparation of the seed-bed, as well as the time, depth, and manner of subsequent cultivation, is judged entirely by the increase or decrease in growth and yield of the above-ground parts with scarcely a thought as to the more direct cause, the effect of these practices upon root activities and development. It should be clear that a knowledge of root development under each of the diverse methods of tillage, systems of mulching, etc., will not only give a logical answer for the results obtained by these practices, but will form a scientific basis for the application of other methods or combinations which may result in greater yields.

Crop rotations on different types of soil and under different climatic conditions should be worked out with constant reference to root relations. It may be found practicable, especially in semiarid regions, to grow short-rooted and densely-rooted crops alternately with those of longer and more spreading root systems. In humid regions, under intensive agricultural conditions, two such crops might be grown in the same field at the same time. In fact, this is a common practice in India, where mixed cultures usually outyield pure ones. The selection, breeding, and adaptation of crops for arid and semiarid regions should logically center about their efficiency as absorbers and conservers of water. Plasticity of root systems as to depth, lateral spread, degree of branching, etc., goes far toward determining the ability of a crop to make sufficient growth and yield to warrant its cultivation in dry lands. Moreover, under these conditions root competition is an important factor in determining the rate of seeding.

It seems not improbable that some of our best yielding crops may be able to outstrip others largely because of their greater efficiency in securing a larger and more constant supply of water and nutrients. Why certain artificial mixtures of grasses and other herbs may thrive in pastures and meadows, while others do less well, must depend to a large degree upon competition of root systems. This is the case in native grassland, where it is usual for 200 to 300 individuals or groups of individual plants to grow in a single square meter, due to lessened competition resulting from absorption at different soil-levels and from maximum above-ground activities at different times of the growing-season.

Just as a knowledge of root systems of native plants makes far more exact their value as indicators of lands with the possibility of crop production, likewise this knowledge of underground parts is of great value in solving problems of soil erosion, whether by wind or by water. This holding of the soil for cultivation applies equally to plants of pasture and meadow lands and to a certain extent to annual crops. Likewise, keeping the soil free from noxious weeds, and especially perennials, is again a problem concerned primarily with underground plant parts.

The relation of the disease resistance of crop plants to root development is an important one and warrants thorough study. Recent investigations

have demonstrated a close relation between the vigor of root growth and disease resistance. Where the disease is physiological, resulting from malnutrition or insufficient aeration, this relation is at once apparent. It seems certain, in the light of recent investigations, which show the extensive nature of the roots of most crop plants, that the results of many experiments, where plants were grown in pots or even relatively large containers, may have more apparent than real values when the work is repeated under field conditions. A thorough study of root distribution and absorption under cropping conditions will throw much light upon the relative value of greenhouse experiments on soil fertility, where containers of various sizes with either surface soil or subsoil were used. Even plant-breeding or crop-production experiments conducted in the field in small adjacent plats or by the row per ear or head method, undoubtedly have been affected and the results in many cases vitiated by the factor of root competition.

The importance of a thorough investigation of root development and root activities need not be pointed out in greater detail. In preceding volumes (Weaver, 1919, 1920) the relation of a knowledge of root systems to plant production in its broader sense has been emphasized. The underground parts of 1,500 native plants of forest, chaparral, sandhills, plains, and prairie have been studied with a view to acquiring fundamental knowledge of value in the solution of many problems of crop production. Outstanding among these are range management and improvement, involving that complex phenomenon termed plant succession; afforestation and reforestation; and indeed the whole problem of land classification based upon indicator significance of native vegetation. Such studies through an extended region, such as our grassland formation, afford an excellent background for investigations of crop plants grown in any part of the area. For a knowledge of root position of native plants, especially when interpreted in their community relations, so clearly reflects the moisture conditions of the soil that it aids not only in selecting the kind of crop to be most profitably grown, but also helps in determining the proper methods of tillage. This is especially true when the root habits of crop plants are also known and the degree to which they are modified by the environment. An extended study of the root systems of cereals from the Missouri to the Rocky Mountains has been reported and their growth habits correlated with the environment as indicated by the native vegetation. Moreover, the variations of root development of many species of crop plants on upland and lowland have been worked out in a preliminary manner (Weaver, 1920).

This book may be considered a continuation of "Root Development in the Grassland Formation." The investigations here recorded were carried out during the growing-seasons of 1919 to 1921. Stations were selected at Peru and Lincoln, Nebraska, at Phillipsburg, Kansas, and at Burlington, Colorado. These stations have a mean annual precipitation of about 33, 28, 23, and 17 inches, respectively. The differences in climate are clearly expressed in the type of natural vegetation. The true prairies at Lincoln give way southeastward along the Missouri near Peru to the subclimax prairie, which is potentially chaparral or woodland, the grasses having possession only because of such disturbances as grazing, fire, mowing, etc. At Burlington, in eastern Colorado, a typical expression of the short-grass plains is found, while in

north-central Kansas at Phillipsburg short-grasses intermingle with the taller ones and constitute mixed prairie (Clements, 1920, 114; Weaver, 1920, 12). Crops were grown at the several stations under measured environmental conditions for the purpose of determining not only the nature of the root system, but especially also its distribution and extent at various stages of growth. The work was conducted under field-crop conditions and methods of tillage in order that the results might faithfully portray the root relations of crops as grown under usual farm practice. Moreover, extensive experiments have been conducted both in the greenhouse and under field conditions to determine the active working-level of the roots of cereals and other crop plants as regards the absorption of water and nutrients at various stages in their growth.

The method used in excavating root systems was the same as that employed during the past six years. By the side of the plants to be examined a trench was dug to a depth of about 5 feet and of convenient width. This affords an open face into which one may dig with a hand-pick and other appropriate apparatus and thus make a careful examination of the entire root system. This apparently simple process, however, requires much practice, not a little patience, and wide experience with soil texture. In every case several plants were examined, often 10 or more at any given stage of development, to insure an adequate idea of the general root habit. Among this number it was possible to secure some root systems in their entirety. In cases where reconstruction was necessary, this was rendered more accurate and less difficult by methods of record in the field. As the work of excavation progressed, the trench was deepened, so that finally the soil underlying the deepest roots was undercut for several inches and carefully examined as it was removed to assure certainty as to the maximum depth of the root-ends. Frequently the trenches reached depths of 5 to 9 feet.

The usual practice was followed of writing a working description of the root system after several plants had been examined and then noting any variation from this description as more roots were excavated. This checking of the description in the field leads to a high degree of accuracy, for if any point regarding the root habit remains indefinite, opportunity is offered for further study. This is absolutely essential in developmental studies.

Drawings of the root systems were made with pencil in the field on a large drawing-sheet and then retraced with India ink. They were made simultaneously with the excavating of the roots and always to exact measurement. In the drawing the root systems are arranged as nearly as possible in the natural position in a vertical plane; that is, each root is placed in its natural position with reference to the surface of the soil and a vertical line from the base of the plant. In the case of potatoes the roots were so abundant that to depict all of them led to confusion, so that in the drawings of these plants only one-half of the root system is shown.

In every case it was sought to illustrate the average condition of root development rather than the extreme. Although the drawings were made on a large scale, the rootlets were often so abundant that it was quite impossible to show the exact number as determined by average root-counts. Such drawings, however, carefully executed, represent the extent, position, and minute branching of the root system even more accurately than a photograph,

for under the most favorable conditions, especially with extensive root systems, the photograph is always made at the expense of detail, many of the finer branches and root-ends being obscured.

The writers wish to acknowledge the faithful assistance of Miss Annie Mogensen and Mrs. F. C. Jean in the execution of the drawings of the root systems. Grateful acknowledgment is made to Professor J. C. Russel, of the Department of Agronomy of the University of Nebraska, for many helpful suggestions in connection with the analyses of soils and the experiments con-concerning the absorption of nutrients, as well as for the generous use of his laboratories in pursuing this phase of the work. To Mr. O. R. Clark we are indebted for valuable field assistance during 1920, and to Mr. E. Y. Lipetz for the translation of certain papers from the Russian. It is a pleasure to acknowledge the helpful suggestions given by Dr. F. E. Clements and Dr. R. J. Pool throughout the period of the work. To both Dr. Clements and Professor T. J. Fitzpatrick the writers are indebted for the reading of the manuscript and proof.

I. INVESTIGATIONS AT PERU, NEBRASKA, IN 1919.

Studies of the root development of plants at Peru were conducted during the season of 1919. The crops used were as follows: two strains of oats (*Avena sativa*), White Kherson and Swedish Select; two species of wheat, Durum (*Triticum durum*), and Marquis Spring (*Triticum æstivum*); Manchuria barley (*Hordeum vulgare*); Early Ohio potatoes (*Solanum tuberosum*); and Iowa Silver Mine corn (*Zea mays indentata*). These were grown on an upland area of silt-loam soil, which lay near the top of a hill on a gentle western slope. The field, which had formerly been a bluegrass pasture, had been broken three years previously and the plants grown for these investigations were a fourth crop. Potatoes had been grown the preceding year, and the soil was in excellent tilth when the crops were planted. The surface 1 to 1.5 feet consisted of a dark-colored silt-loam. This was underlaid by a very mellow loess to a depth of many feet.

The crops were planted in plats 200 feet long and 30 feet wide, each containing approximately 0.14 acre. These extended in an east-and-west direction. Corn and potatoes occupied the plats on the south side of the field. The smaller cereals were planted with a grain-drill at a depth of about 4 inches. The rate of seeding in pounds per acre was as follows: University oats 64, Swedish Select oats 48, barley 48, Marquis spring wheat and Durum wheat, 60. The corn was drilled in rows 3 feet apart at a depth of 3.5 inches, the kernels being placed 1.4 feet apart in the row. The potatoes were also planted in rows 3 feet apart, the space between the sliced tubers being 2 feet. They were covered with 3 inches of soil.

Preparatory to planting, the plats were plowed to a depth of 5 or 6 inches on March 29 or April 4, and immediately harrowed. All of the crops, except corn, were planted at once without further preparation of the seed-bed. The latter was planted on May 9, after the plat had again been harrowed.

University No. 21 Oats, Avena sativa.

This is a special strain of the Kherson oats developed and named by the Department of Agronomy at the University of Nebraska College of Agriculture. It is known especially for its heavy yielding qualities.

The first examination of this oat was made April 18, 18 days after planting. Each plant had a single leaf, which had been above ground about 8 days and had an average height of 1.5 inches. The number of roots was 3 or 4. In most plants there appeared to be a main root that took an almost vertically downward course. In position it resembled a tap-root, but in structure and appearance was not unlike the others. Its length varied from 4 to 6 inches and all its characters indicated that it was the primary root. The other roots, while taking a general course downward, did not follow the perpendicular so closely. Instead, they descended at various angles from the vertical to a distance of 1 to 5 inches. In some cases they ended 3 inches from the vertical and 3 to 6 inches below the surface. No branches had yet appeared. The roots pursued a gently curving course through the loose soil. They were about 1 to 1.5 mm. in diameter and were densely covered with root-hairs to within 5 mm. of the tips. These hairs were borne so profusely and clung to the soil particles so tenaciously that when the roots were excavated and suspended they presented the appearance of small columns of earth.

Growth conditions during this period were rather unfavorable. Cloudy, wet weather prevailed. At no time was the water-content of the surface foot of soil less than 17 per cent above the hygroscopic coefficient. The temperature of both air and soil was low. The maximum soil temperature of the surface foot did not exceed 62° F. However, the period was free from frost, the lowest air temperature being 37° F.

The second examination of this oat was made May 29, 59 days after planting. The plants averaged 1 to 1.2 feet in height and the number of stalks, including tillers, varied from 1 to 3. The first 7 to 9 inches of soil was filled with a complete network of fine roots and rootlets. Most of these came from a node a short distance below the surface and were branched freely to the first and second orders. They penetrated the soil in all directions from the base of the plant. The branches of all degrees seemed to grow upward as readily as downward, and the tips of those extending upward very often lay just beneath the soil surface. Indeed, it was not unusual to find even some of the larger roots lying at a depth of only 0.5 to 1 inch. The horizontal roots ran outward to a distance of 6 to 12 inches, and then some turned downward. From each plant one or two of the main roots pursued a somewhat irregular course into the subsoil, often reaching depths of 3 to 3.4 feet. The maximum penetration was 3.6 feet. These longer roots were rather densely branched and rebranched, although not to so great a degree as those nearer the surface. Branches of the first order sometimes reached a length of 4 inches. The last 4 to 8 inches of the main roots were unbranched. Figure 1 A shows the two portions of this root system and also indicates how splendidly the plant is equipped for absorption in both the upper and lower layers of soil.

The month of May was cool and dry, and during this second period of root development all of the small cereals grew vigorously. 42 per cent of the days were clear, and there were only 1.8 inches of rain. The day air temperature averaged 65° F., the night temperature 53° F. Records of air temperature were obtained, as at the other stations, by means of Friez's thermographs, placed in appropriate shelters of the Weather Bureau type, with the recording apparatus at a height of 4 inches above the soil surface. Livingston's standardized, white, cylindrical, porous-cup atmometers were employed to measure the evaporating power of the air. The cups were operated in duplicate in the usual manner, with the evaporating surface only 3 or 4 inches above the surface of the soil. Because of the cool weather, the average daily evaporation was only 21 c. c. The soil temperature to a depth of 3 feet averaged 60° F. Although there was a deficit in rainfall of 3.6 inches below the mean, the soil had been so thoroughly wetted during April that samples during May showed an average available moisture-content of 16 per cent in the first 3 feet. The plants had a dark-green color and produced a luxuriant growth of leaves.

A final examination of oats was made July 1, 92 days after planting. The height of the stalks, which averaged 1 to 3 per plant, ranged from 2.8 to 3.2 feet. The crop was about half ripe. In general, the form of the root system was similar to that found at the second examination, except that it was somewhat more extensive. The first 8 or 9 inches of soil were filled with a mass of finely branched roots, many of which extended only a few inches, but

others as far as 1.4 feet from the base of the plant. Thus, the spread of these shallow roots had increased 4 or 5 inches since May 29. These horizontal roots often continued their course near the surface of the soil. Frequently, throughout their whole length, no portion of them could be found that was deeper than 1.5 to 3 inches. Other roots extended almost parallel with the surface for a distance and then turned downward, ultimately reaching depths of 1 to 5 feet. Still others descended almost vertically until they reached depths of 5 to 5.5 feet or more, the maximum length found being 6.7 feet

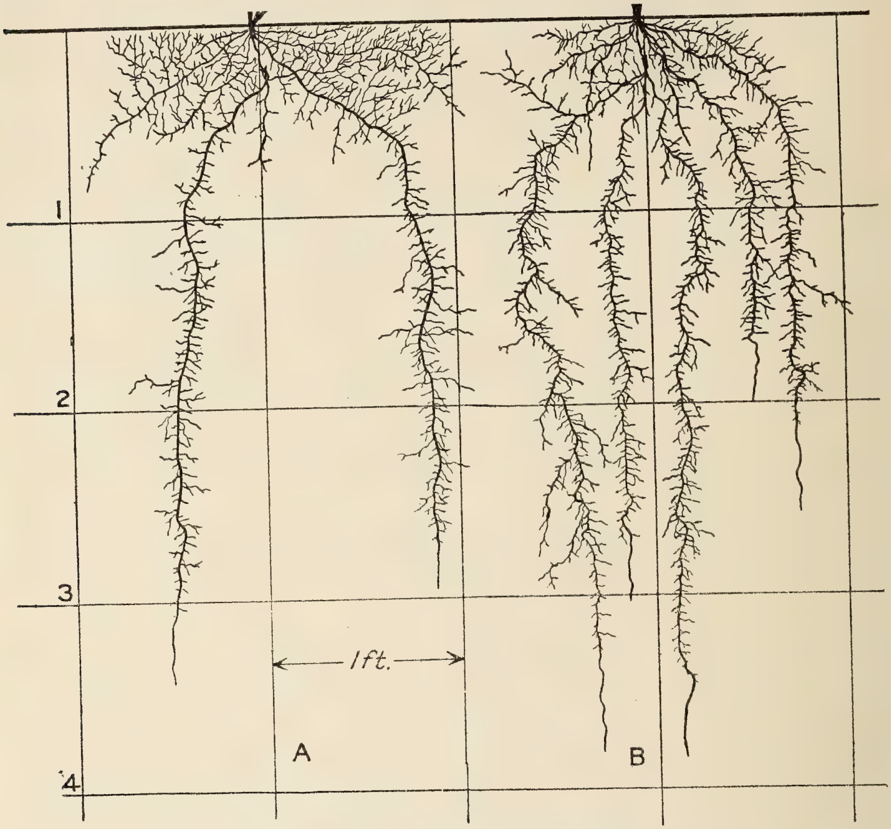


FIG. 1.—A. Root system of University No. 21 oats 59 days old.
B. Swedish Select oats 60 days old.

(fig. 2 A). 5 to 7 of these deeper roots were commonly found. This is an increase of 4 or 5 over those present at the time of the preceding examination. The roots were all profusely branched with fine branches ranging from 0.1 to 4 inches in length. This was especially true of those lying near the surface, where the branches were longest. On practically all of the roots at this time the branches extended almost to the tips. The roots were very fragile, especially the deeper ones. The shrunken and shriveled cortex indicated that considerable material had been transported from them. The soil was fairly well filled with roots to a depth of 3.8 feet, and below this to 5.4 feet they were quite numerous. Thus, it is evident that the root system of this

oat is splendidly adapted not only for absorption in the surface soil, but also at much deeper levels. This extensively developed root system undoubtedly plays no small part in making this strain of Kherson oats one of those best adapted to the semiarid condition of Nebraska.

Growth conditions during June were very favorable. The mean day and night temperatures were 74° and 64° F. respectively. The mean temperature of the first 3 feet of soil was 74.6° F. The rainfall was 4.3 inches, while about 56 per cent of the days were cloudy. Hence the relative humidity was rather high. The average daily evaporation for the month was 24 c. c. Water-content determinations on June 23 and 28 showed a margin of about 6.5 per cent above the hygroscopic coefficient in the first 3 feet of soil. Except for clear, dry weather during the last 10 days of this period, conditions were such as to stimulate a very luxuriant vegetative growth. However, the plants stood up well till the grain was ripe. The yield was at the rate of 62.5 bushels per acre. The yields of the small cereals were based upon the yield by weight of a single square rod selected from a representative portion of each plat.

Swedish Select Oats, Avena sativa.

The root system of the seedling stage of this plant was studied on April 19, 19 days after the seed had been planted. Each plant had a single leaf about 1.5 inches long, which had been above ground about 9 days. 3 or 4 roots grew out from the hypocotyl. One of these, although not unlike the others in general appearance, took a downward course similar to that of the tap-root, reaching a depth of 10 inches. The other roots, which were 1 to 5 inches in length, descended more obliquely. The roots were about 1.5 mm. in diameter, entirely unbranched, but densely covered with root-hairs. They maintained such an intimate contact with the soil particles that no portion of the excavated root was visible, except the very tips, upon which root-hairs had not yet developed. Environmental conditions of the several intervals of growth have already been given in the discussion of University No. 21 oats.

The root system was again examined 60 days after planting. The crop had reached a height of 10 to 12 inches, and the number of stalks, including tillers, varied from 1 to 4 per plant. The roots originated both from the old kernel and from a node just below the soil surface. Most of the roots either pursued a course almost vertically downward or ran off obliquely to a distance of 6 to 10 inches and then turned downward with a long, graceful curve (fig. 1 B). A few were short and ran almost parallel with the soil surface, where their ramifications terminated 6 to 10 inches from the base of the plant. The deeper roots penetrated to depths of 3.2 to 3.5 feet, with a maximum of 3.7 feet. The roots to within about 8 to 12 inches of the tip were copiously branched. These branches varied in length from a few millimeters to 5 or 6 inches and the relative number of the longer branches was unusually large. The laterals of the first order were in turn often branched and rebranched. The deeply penetrating roots were usually from 4 to 6 in number, while shallower ones varied from 4 to 7, or even more.

The last investigation of the underground parts of this plant was made July 2. This was 93 days after the seed had been planted and when the crop was beginning to ripen. Each plant had from 1 to 3 stalks, with an average

height of about 3 feet. The mature root system bore a strong resemblance in form to that found at the last examination. It was characterized by the large number of deeply penetrating roots. Some of these ran almost vertically downward from the base of the plant, while others went out obliquely to a distance as great as 12 inches and then turned downward with a gradual

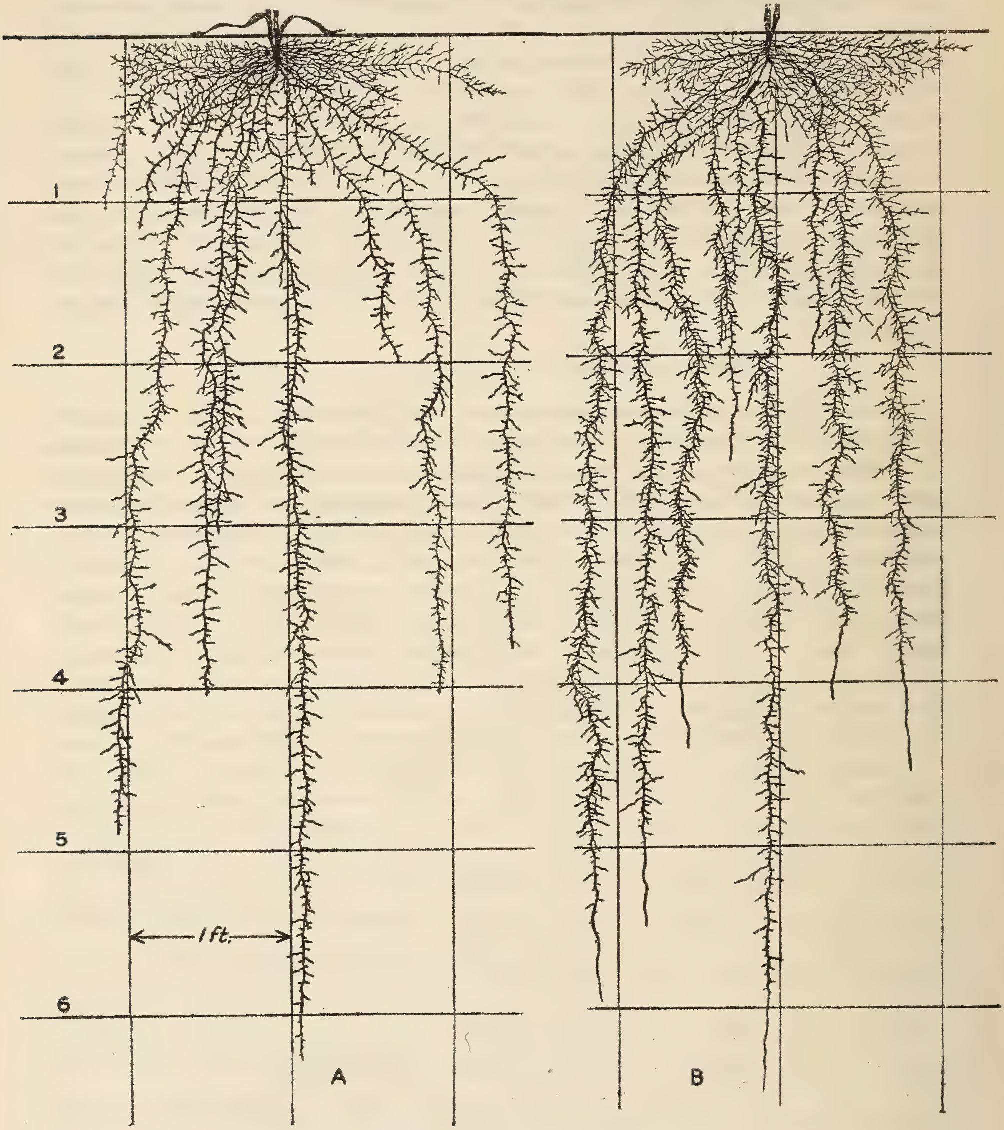


Fig. 2.—A. University No. 21 oats at maturity.
B. Swedish Select oats at maturity.

curve. Other roots took positions intermediate to these extremes (fig. 2 B). The number of these deeper roots varied from 7 to 11. They pursued a rather tortuous course. The usual depth of penetration ranged from 2 to

6 feet or more, while the maximum depth was 6.8 feet. The soil was well filled with these roots to a depth of 4.6 feet; many reached depths of 5.5 to 5.8 feet below the surface. They were profusely branched to the second order; the length of the branches varied from 0.3 to 5 inches. The last 6 to 8 inches of the roots were unbranched.

The superficial system was composed of much finer roots, which ran nearly parallel with the surface or took a slightly oblique course. The longest of these were from 1 to 1.3 feet. They were profusely branched and rebranched with fine rootlets, which extended in all directions from the main root. Branches of the first order were sometimes 4 to 5 inches long. In many instances their ends were found just below the dry, dusty surface of the soil. The shallower roots were developed only to a moderate degree at the second examination, but as the time of maturity approached this portion of the root system continued to grow and extend its area markedly. At no time, however, did its extent and density even closely approximate that of the University No. 21 variety (*cf.* figs. 1 and 2).

Summarizing, this oat is characterized by a well-developed, deeply penetrating and profusely branched root system. The depth of penetration of so many of the larger roots may be correlated with the luxuriant growth of tops. This brings about a balance between absorption and transpiration. This oat grew rank and produced heavy straw. The plat yielded at the rate of 40 bushels per acre, but the quality of grain was only fair, because of the presence of many light kernels, due in part to an attack of *Puccinia graminis avenæ*.

Durum Wheat, Triticum durum.

The first examination of Durum wheat was made 19 days after sowing. The plants had been above ground about 9 days and had but one leaf unfolded. They were approximately 3 inches tall. The root system consisted of 4 or 5 roots, usually 5, which ranged in length from 1.5 to 8 inches. While some in their descent made only small angles with the vertical, most of them pursued a more oblique course downward, and, compared with their length, spread rather widely from the base of the plant. In some instances the tips of the roots were 4 or 5 inches from the vertical. Secondary branches varying from 2 to 8 in number had begun to appear on some of the older roots along the first 1 to 1.5 inches of their course. They looked like tiny white threads only 2 to 3 mm. long. They were rather tough in texture and, with the exception of the extreme tips, fairly well covered with root-hairs.

The second excavation was made on May 30, 60 days after the date of planting. The crop was from 8 to 12 inches high, and each plant had from 1 to 4 shoots. The roots were extremely fine and fibrous and showed more or less distinctly two types—a surface-feeding type and a deeper absorbing one. Regarding the latter, it is of interest to note that Robbins and Rotmistrov are not in accord as to their point of origin. In discussing the primary roots that spring from the region of the hypocotyl, Robbins (1917 : 91) states: "This whorl constitutes the primary or temporary root system. It usually dies before the plant is full grown." Rotmistrov (1909 : 32), in referring to the smaller cereal crops in general, says: "These primordial rootlets continue to be main roots or roots of the first order during the whole period of vegetation which follows."

The root systems of the wheat plants examined agreed with the statement of Rotmistrov, for not only at this period did these primary roots penetrate deepest, but they lived and continued to grow and function until the plant matured, at which time they had reached greater depths than any of the roots that formed later (fig. 3 c). Of these primary roots a few grew almost vertically downward, but by far the greater number passed off obliquely to a distance of 0.5 to 1.3 feet and then, turning downward, pursued a zigzag but generally vertical course to a depth of 3.9 to 4.2 feet. The maximum depth

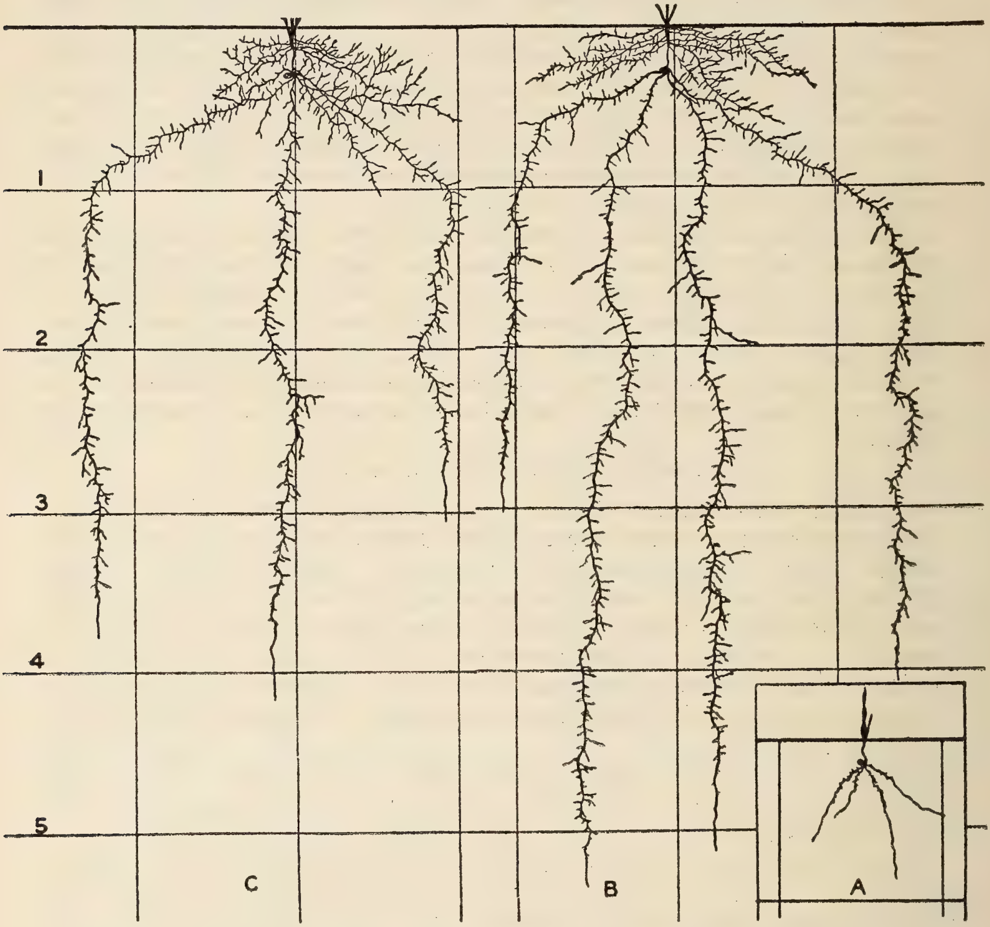


Fig. 3.—A. Marquis wheat 20 days old; B. 70 days old. C. Durum wheat 60 days old.

of penetration was 4.5 feet. These main roots were yellowish in color and quite tough. Throughout their course, excepting the last 8 to 12 inches, they were quite abundantly branched, the branches varying from a few millimeters to 2 or more inches in length. These branches were themselves often rebranched. Just below the surface of the soil another set of roots arose from a node on the main stalk. These passed out almost horizontally in all directions to a distance of 6 to 8 inches. Some of these, however, were

just beginning to push out from the node, while between these extremes roots of all intermediate lengths were found. They were fairly well branched to the second order; the branches extended in all directions and ranged from 0.2 to 2 or 3 inches in length, according to their age.

A final root examination was made July 4, 95 days after the wheat had been drilled. The plants were 2.2 to 2.8 feet high and averaged two stalks each. The grain was in the stiff-dough stage and the heads had begun to turn yellow. Relative to the other smaller cereals, this plant had a rather meager surface-feeding system at maturity. Usually this consisted of 6 to 8 (rarely more) roots that extended out in an almost horizontal direction (fig. 4 A). They varied in length from 2 to 14 inches and ended only 4 to 7 inches below the surface. They were fairly well supplied with rootlets to the second and third orders. The primary roots, as determined at the previous examination, continued to be the most pronounced portion of the root system. From their points of origin they ran either vertically downward or downward and outward until they reached a distance of 0.4 to 1.3 feet from the vertical, where they turned downward, pursuing a more or less zigzag course. A few of the roots which originated from the node above the old kernel, and which at the second investigation had a course more or less horizontal, had now turned downward and penetrated deeply. All the roots were well supplied with branches from a few millimeters to 3 or 4 inches or more in length. These laterals were rebranched. The soil was especially well filled with roots to the fourth foot; many also occurred in the fifth and sixth foot, and not a few extended even deeper. The maximum depth to which roots extended was 7.4 feet. Due to an attack of stem rust (*Puccinia graminis tritici*), this wheat yielded at the rate of only 8 bushels per acre. Moreover, there were many shriveled kernels, which made the grain of rather inferior quality.

Durum wheat, when grown under the conditions described, has a surface root system of only medium extent, but a large, extensive portion which penetrates very deeply. These studies show clearly, moreover, that the root system develops coordinately with the above-ground parts, for it is only in this way that the increasing demands of the developing shoot for water can be successfully met.

Marquis Wheat, Triticum æstivum.

The roots of this plant were examined April 25, 20 days after planting. Most of the plants had shown above ground for about 9 days. The tops were 2 to 2.5 inches high and the second leaf had just begun to unfold. Three or four roots had developed. Their courses varied widely. Some had grown almost straight downward, others diverged at wide angles from the vertical, while still others had taken an intermediate position with reference to these extremes (fig. 3 A). The number of roots varied from 3 to 5, but most of the plants had 4. The maximum spread from the vertical was 7 inches; the greatest depth of penetration was 11 inches. The roots ranged in length from 5 to 9 inches. They were light in color, had a diameter of a millimeter or less, were rather tough, and all their surface, excepting the very tip, was covered with a copious growth of root-hairs. For a distance of 2 to 3.5 inches from the base of the longer roots, branches had begun to appear. The longest of these, however, did not exceed 0.5 inch.

Root development was again determined on June 14, 70 days after the crop had been planted. The wheat was 1.5 to 2 feet tall and the stems had begun to joint. Each plant had from 2 to 4 stalks. The root system was characterized by a shallower portion, consisting of 9 to 14 roots, which

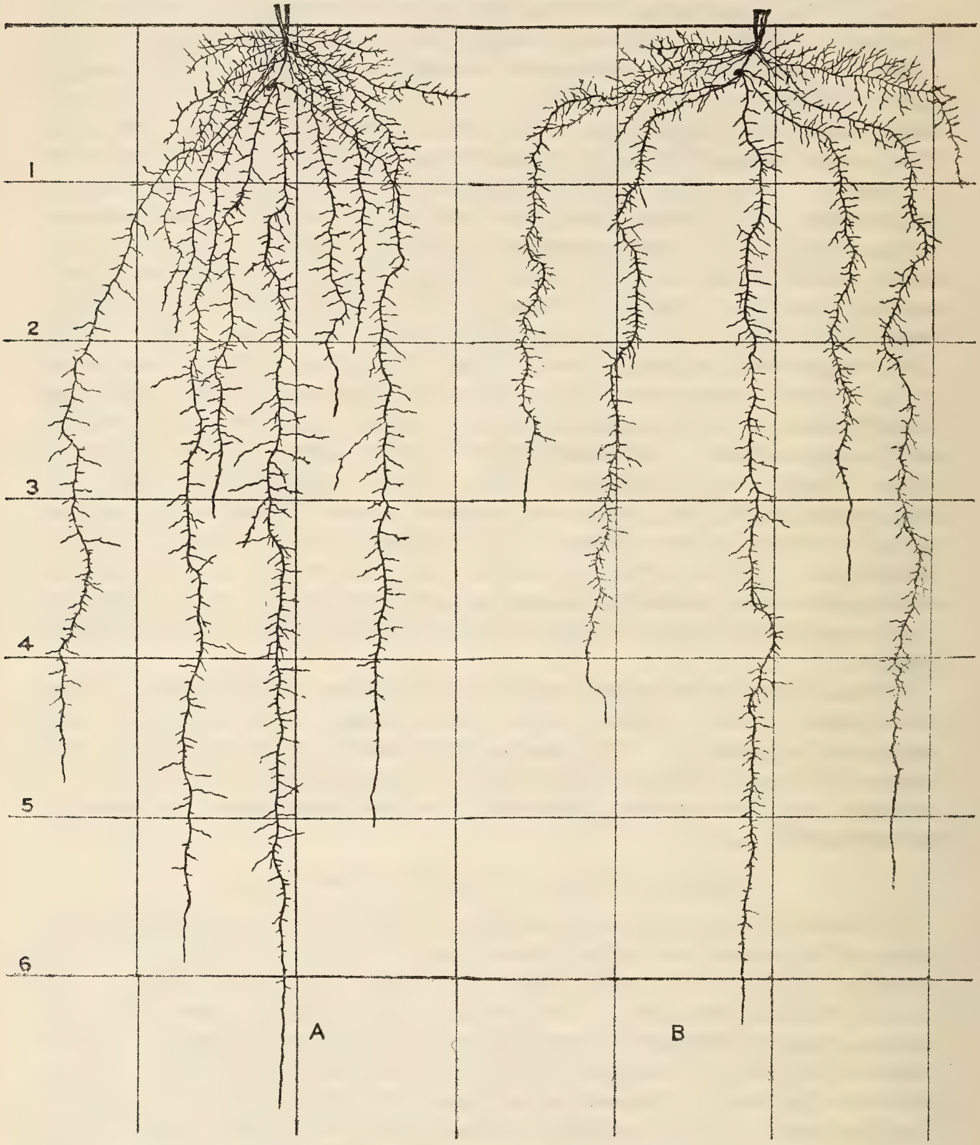


Fig. 4.—A. Durum wheat at maturity.
B. Marquis wheat at maturity.

originated from the nodes of the stalks below the soil surface. These roots ran horizontally, or very nearly so, to a distance of 3 to 10 inches from the base of the plant. They ended from 2 to 8 inches below the surface. They

were fairly well branched to the second order with delicate branches that extended in all directions and formed a network (fig. 3 B).

The part of the root system which penetrated deeper consisted of 3 to 5 roots. They originated very near the old kernel. Some of them ran almost straight downward to a depth of 4.8 to 5.5 feet. The maximum depth was 5.8 feet. Others wandered off rather obliquely to a distance of 0.6 to 1.3 feet and then took a vertically downward course. These roots that spread more widely did not penetrate so deeply, but ended at the 2.5 to 4.5 foot level. All portions of the deeper roots, except the last 6 to 8 inches, were well supplied with fine, often rebranched laterals. The soil was fairly well filled with these main roots and their branches to a depth of from 4 to 4.6 feet.

The last examination was made on July 7, 93 days after the planting. The height was from 2.5 to 2.8 feet, and the plants averaged about 2 stalks each. The grain was in the stiff dough and the heads had just begun to ripen. The shallower portion of the root system was not markedly developed; in fact, scarcely more so than at the preceding examination on June 14. It consisted of 9 to 14 roots that took their origin from nodes on the stalk below the soil surface. These either extended laterally quite parallel with the soil surface or took a downward and outward course, thus extending in all directions from the base of the plant. They varied in length from 0.2 to 1.7 feet (fig. 4 B). While they were quite well supplied with branches from a few millimeters to 3 or 4 inches long, these were not copious. The longer laterals frequently rebranched. The roots that penetrated deeply, usually from 3 to 8 in number, either ran vertically downward from the old kernel or at a depth of 4 to 6 inches took a course obliquely outward to a distance of 4 to 16 inches and then turned downward. Of these roots there were generally one or two more than at the time of the second examination. They were well supplied with branches, except the last 8 to 14 inches, where laterals occurred only rarely or not at all. These branches varied in length from 1 mm. to 2 or 3 inches. The diameter of the main roots was approximately 1.5 mm. The soil was well filled with these roots and their branches to a depth of 3.7 to 4.2 feet. Roots were frequent even at a depth of 5 feet, while some reached a maximum depth of 6.7 feet.

A survey of these data shows that, while this wheat is provided with a root system fitted to absorb both in the surface as well as in the deeper soil, under the conditions of growth in this experiment the shallower portion was not highly developed. The number and extent of the longer roots, together with their great depth of penetration, is a marked feature and is especially impressive when the extent of the underground parts is compared with height of tops. The yield of Marquis wheat was at the rate of only 3.7 bushels per acre. It was planted a week later than the Durum wheat and was somewhat more susceptible to the epidemic of stem rust which swept over much of the Missouri Valley in the summer of 1919. The plants were attacked just before blooming, and by the time the grain was going into the dough stage the surface of the leaves and stems was covered with rust pustules. This resulted in very light, shriveled kernels.

Manchuria Barley, Hordeum vulgare.

The barley roots were examined the first time April 25, 20 days after the seed had been drilled. The plants had shown above ground about 8 days. They averaged 5 inches in height and the second leaf was just beginning to unfold. In this early state of growth, however, the root system showed a marked tendency to develop into two rather distinct portions. One set of roots grew at once toward the subsoil, while the other ran off quite horizontally. Of the former lot there were two or three on every plant. Quite regularly one of these, not unlike the others in structure or general appearance, took a course so vertically downward as to constantly remind one of a tap-root. The others, while nearly always growing rather straight downward, occasionally wandered off in an oblique direction to a distance of 6 to 9 inches from the perpendicular and finally reached a depth of 0.7 to 1.2 feet. Small branches had appeared on the older portions of the roots to a distance sometimes as great as 4.5 inches from the base of the plant. The branches did not exceed 0.5 inch in length.

The other portion of the root system consisted of four or five roots which usually took an almost horizontal course through the soil. Occasionally one or two of these even curved up slightly towards the surface. Many reached a length of 4 to 8 inches and ended only 3 or 4 inches below the soil surface. This portion of the root system was also branched quite sparingly. However, the branches occurred to within an inch of the root-tips. The roots were a millimeter or less in diameter, light in color, rather elastic, and quite well covered with root-hairs to within a short distance of the tip (fig. 5 A).

The second examination was made on May 29, 54 days after planting. The number of stalks per plant, including tillers, varied from 2 to 4. The height ranged from 9 to 12 inches. Barley, as was true of all the small cereals at the time of the second examination, had thrown out roots from two distinct points, the original ones from the hypocotyl and the second group from a node just below the surface of the soil. The shallower and deeper portions of the system already noted were still maintained (fig. 5 B). The roots composing the former extended out almost horizontally in all directions from the base of the plant, or had only a slightly downward course. In number they ranged from 8 to 12, were from 5 to 16 inches long, and ended from 2 to 10 inches below the surface of the soil. These shallower roots were profusely branched and rebranched to the second and third orders with thread-like branches varying from a few millimeters to 3 or 4 inches in length. The first 6 to 8 inches of soil were densely filled with these horizontal roots and their network of branches.

The second type of roots penetrated deeply. Two to four occurred on each plant. The depth of penetration was usually from 3.7 to 4.2 feet, although some reached the 4.5-foot level. These main roots frequently took a vertical course, but as often wandered obliquely from the base of the plant to a distance of 8 to 10 inches and then ran irregularly downward. These roots were profusely branched within the first 3 feet of soil; sometimes as many as 20 branches occurred on a single inch. The last 6 to 8 inches were not branched. The old roots near the base of the plant were hard, wiry, and yellowish in color, while the new ones were crisp and white. None of them, at this point, were more than 1 mm. in diameter. As a rule, the diam-

eter of the younger portions was somewhat greater, due to their greater succulency.

The mature root system of barley was studied on June 28, when the plants were 84 days old. The crop was from 2 to 2.5 feet high and each plant had 2 to 3 stalks bearing heads. The crop was ripening rapidly and was harvested 5 days later. It yielded grain of good quality at the rate of 25.8 bushels per acre. The shallower portion of the root system was practically the

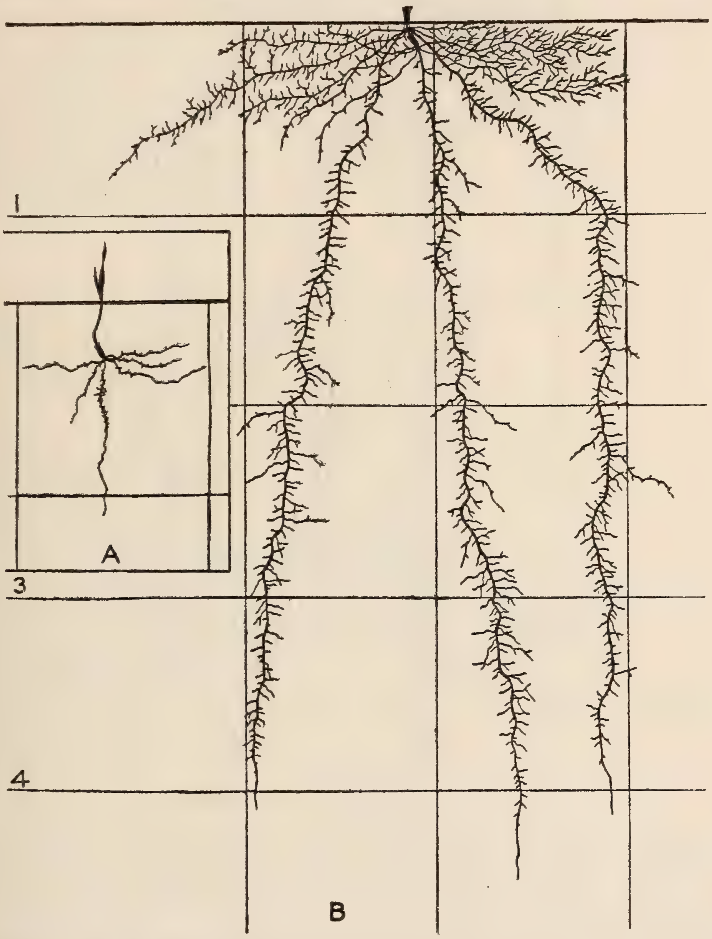


Fig. 5.—A. Manchuria barley 20 days old; B. 54 days old.

same as at the time of the second examination on May 29. The greater part of it originated from the stalk above the old shrunken kernel and spread out horizontally at a depth of 2 to 10 inches below the soil surface. These roots varied from 0.1 to 1.3 feet in length. They were rebranched only to a moderate degree.

The primary roots that took their origin from the hypocotyl constituted the part which penetrated deeper. However, there were some exceptions. Occasionally a root which had developed later from the node on the stem

turned downward and penetrated deeply into the subsoil (fig. 6). Some of the roots, just described, descended almost vertically, others ran obliquely outward 0.3 to 1.3 feet and then took a perpendicularly downward course. The soil was fairly well filled with roots to a depth of 3.7 to 4.2 feet, while

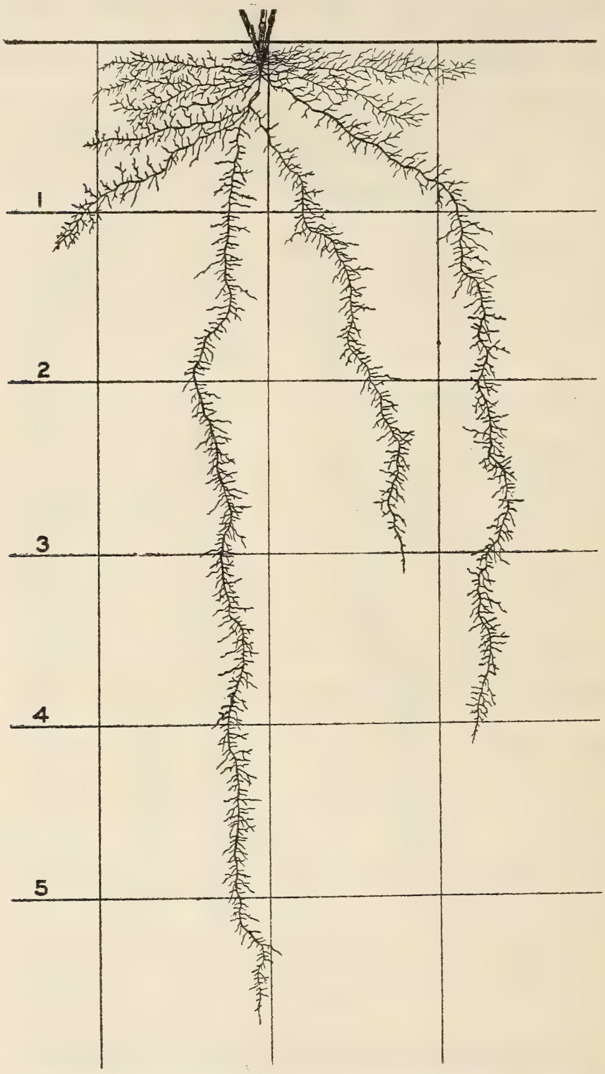


Fig. 6.—Manchuria barley at maturity.

many penetrated to a depth of 5 to 5.8 feet. The maximum penetration was 6.3 feet. The roots were 1 to 1.5 mm. in diameter. They were all abundantly supplied with branches from 0.2 to 2 or 3 inches in length. The branches now extended quite to the root-tips, showing that growth was complete.

Corn, Zea mays indentata.

The corn plat was plowed April 4 to a depth of 4 inches and harrowed immediately afterward. It was harrowed again May 5 to keep it free from weeds, and on May 9 was planted with Iowa Silver Mine corn. This is a large, rather late maturing variety. Before planting, the plat was marked off in rows 3 feet apart and the seed was drilled along the marks without furrowing. The kernels were planted 3.5 inches deep and 1.4 feet apart in the rows. That part of the plat in which the excavations were made was cultivated very shallow with a hoe so as not to disturb the roots. It was hoed three times, on May 31, June 16, and July 9, respectively.

The first examination of the root system was made June 14, 36 days after planting. The height of the crop averaged from 10 to 14 inches and the seventh and eighth leaves were just unfolding. The stand was very uniform. In this early stage of growth it has a distinctive surface system of roots.

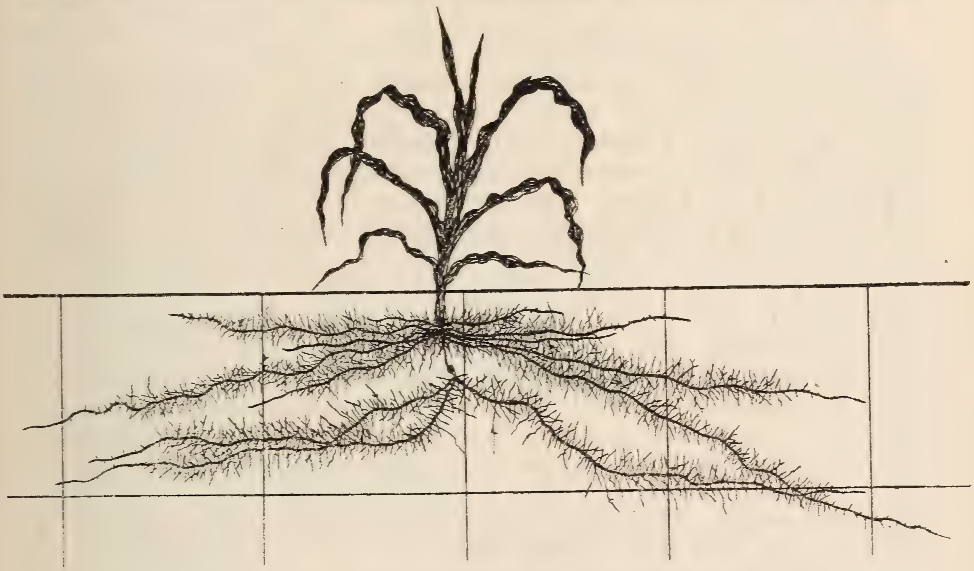


Fig. 7.—Root system of Iowa Silver Mine corn 36 days old.

Of the several plants examined no root approximating the position of a tap-root was found. Whether originating from the hypocotyl or from a node above, the roots took a course parallel or almost parallel with the surface of the soil. In this manner they ran out in all directions from the points of origin. The number of roots varied from 10 to 15; they were about 1.5 mm. in diameter, and ranged in length from 0.1 to 2.6 feet. They ended from 0.2 to 1.3 feet below the surface (fig. 7). Throughout their length, excepting the last 8 to 12 inches, all the roots were profusely branched and as many as 33 rootlets were counted on a single inch. The branches varied from a few millimeters to 4 inches in length and were themselves rebranched.

*This period had been very favorable for plant growth. Although May was somewhat dry, the precipitation during the first half of June was greater than normal. The available water-content to a depth of a foot averaged

12 per cent. The soil was in fine tilth and warmed up rapidly. The average soil temperature to a depth of 1 foot was 63° F. The above-ground conditions were also favorable. The mean daily temperature was about 64° F. The last half of May was clear and dry and the first half of June was cloudy, but warm. The daily evaporation for the period in May was 24 c. c., but for June, due mostly to cloudiness and an increased humidity, it dropped to 20 c. c. Thus, the environmental factors, both aerial and within that part of the soil occupied by the roots, were conducive to rapid growth. The corn plants responded favorably to these conditions, as shown by the fact that within a period of 36 days from the date of planting they had reached an average height of 12 inches.

The second examination of the corn roots was made July 5, 57 days after planting. The stalks were about 4 feet tall and 4 or 5 nodes were visible (plate 1 A). During the period intervening between the first and second excavations, a remarkable extension of the root system had taken place. It now consisted of two rather distinct portions. One of these comprised the original roots, together with those of later development scattered among them and which arose from nodes at very short intervals just above the old kernel. These roots ran out either horizontally or descended very gradually, extending laterally to a distance of 2 to 4 feet from the base of the stalk, where they usually turned downward rather abruptly (fig. 8). They penetrated to a depth of 1.5 to 4.6 feet. The other portion of the root system consisted of a large group of roots of later development that ran almost vertically downward or spread out only a short distance from the base of the plant and then took a downward course. The spread of these roots was seldom more than 10 or 12 inches from the vertical. They were the youngest roots, growing vigorously, and were found in all stages of development. Some were just starting from the base of the plant, while others had already penetrated to a depth of 4.7 feet. They were succulent and turgid and had a diameter of 3 or 4 mm. or more. Both groups of roots were well supplied with branches, those lying near the surface were most profoundly branched. These branches were in turn often branched and rebranched to the third and fourth orders. The longer branches were confined to the first foot of soil and, with their many ramifications, formed a wonderfully dense and efficient surface absorbing portion of the system. Below the first foot the branches from the main roots were shorter, usually not exceeding 4 or 5 inches. In color the roots were either brown or white, depending upon their age. The last 6 to 12 inches of the growing tips were pearly white and devoid of branches.

This period was more favorable for growth than the preceding. Both air and soil were constantly growing warmer. The mean daily air-temperature was 75° F. The soil-temperature, taken for the first 8 days of the period only, reached 76.3° F. as an average for the first 3 feet by June 23. This was 11° F. higher than the reading of June 9. The precipitation was about normal, and the first 3 feet of soil had an average available water-content of 13 per cent. 60 per cent of the days were clear. The mean daily evaporation was 25 c. c. The crop responded to these highly favorable conditions for growth in a remarkable manner. Although the period was but 21 days in length, the corn increased its height approximately 3 feet, an average

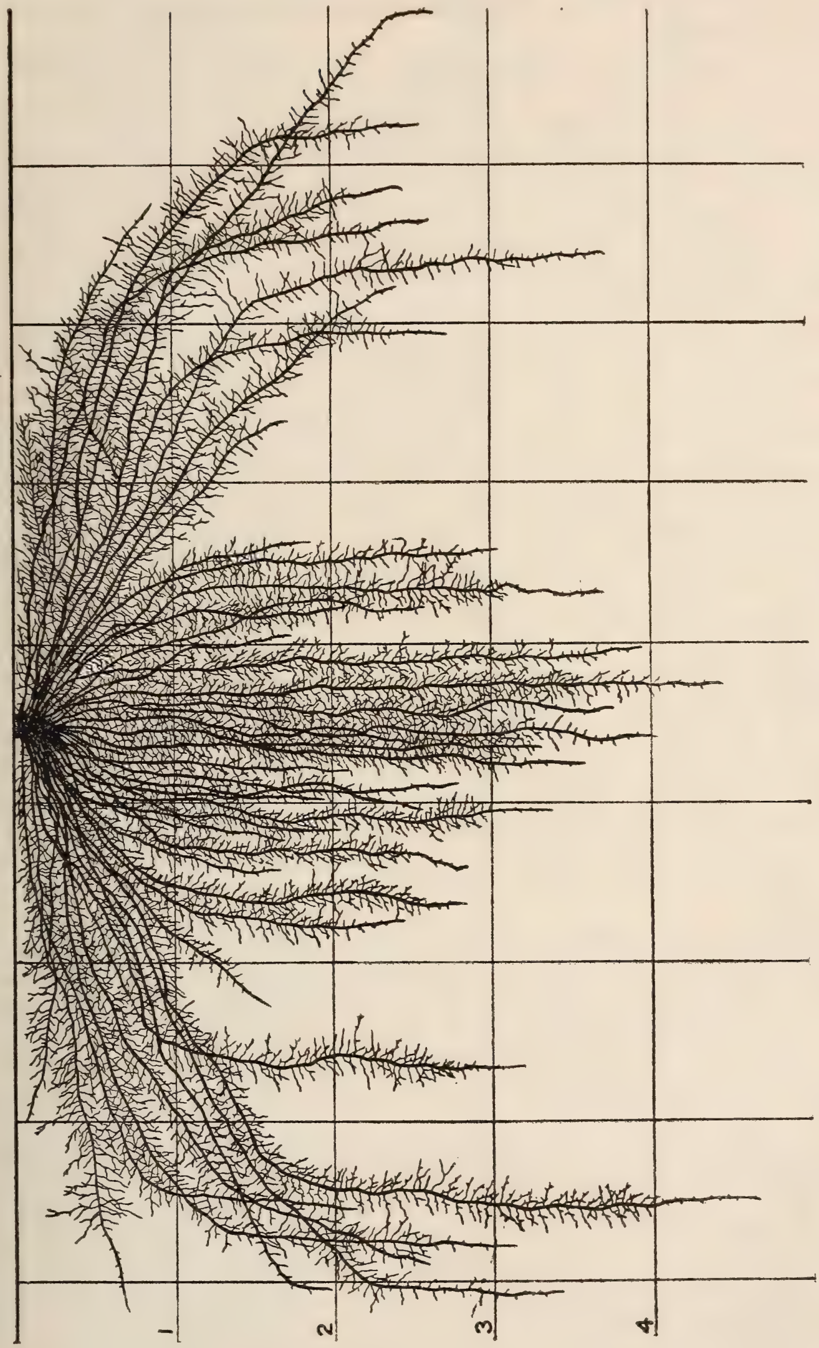


FIG. 8.—Root system of corn on July 5.

daily growth of 1.7 inches. The plants were sturdy and bore an abundance of dark-green leaves.

The root system of the maturing corn plants was examined September 2, 116 days after planting. The stalks were 8 to 9 feet high and, while a few of the leaves had died, most of them were still green. The husks on the ear were just beginning to dry and the kernels were dented (plate 1 c). The shallow portion of the root system had scarcely increased over that found at the July examination, when the plants were 57 days old (*cf.* figs. 8 and 9). Most of the roots of this type were found within the first foot of soil, running in all directions from the base of the plant. Some of them maintained a horizontal position throughout their entire course, which sometimes reached a length of 4 feet. Others ran off at various angles to distances varying from a few inches to as much as 3.7 feet and then turned downward either abruptly or with a gentle curve. They then pursued their irregular course downward to a depth of 2.5 to 3 feet. This surface portion of the root system was profusely branched to the second and third order with branches ranging from less than an inch to 2 feet in length. The surface soil to a depth of 8 to 12 inches was literally filled with these fine rootlets.

Unlike the shallower portion of the root system, the more deeply penetrating part had made a most marked development. On July 5 its growth had just well begun, but by September 2 it had made a really remarkable development. The number of these more vertically penetrating roots varied from about 20 to 35. They either ran straight downward from the base of the plant or obliquely outward to a distance of 2 feet or more, and then with a graceful curve took the perpendicular line of growth. Of these roots a few were short and did not grow deeper than 1 or 2 feet; many reached a depth of 7 feet, while still others were deeper. The maximum depth of penetration was 8.2 feet. At the point of origin these roots were 2 to 5 mm. in diameter. They were all profusely branched with laterals varying from less than an inch to 1.3 feet in length. It was not unusual to find 10 or 12 of these branches on an inch of the main root. The longer laterals were rebranched.

The period intervening between the second and final examination was extremely dry and hot. During the whole interval of approximately two months, the precipitation was only about 2.5 inches, which, with one exception, fell in showers so light as to be of very little value to the crop. The exception was August 25, when the precipitation measured slightly over 0.75 inch. 70 per cent of the days were clear. The average daily temperature for the period was about 82° F. and on several occasions temperatures of over 100° F. were recorded. Due in part to the low humidity accompanying these conditions, the daily evaporation was high. Until July 22 it averaged only 24 c. c., but for the next two weeks interval it reached an average of 41 c. c. daily. Because of these drought conditions the available soil-moisture became greatly depleted. During the part of the period in July the average available water-content for the first 3 feet was 8.7 per cent. On July 29 the fourth and fifth foot of soil had 12 per cent. During August water-content was greatly reduced, the average for the first 3 feet being only 5.6 per cent. On September 2, when the roots were finally excavated, the soil to a depth of 5 feet had only 3.5 per cent of available moisture. The dry soil was

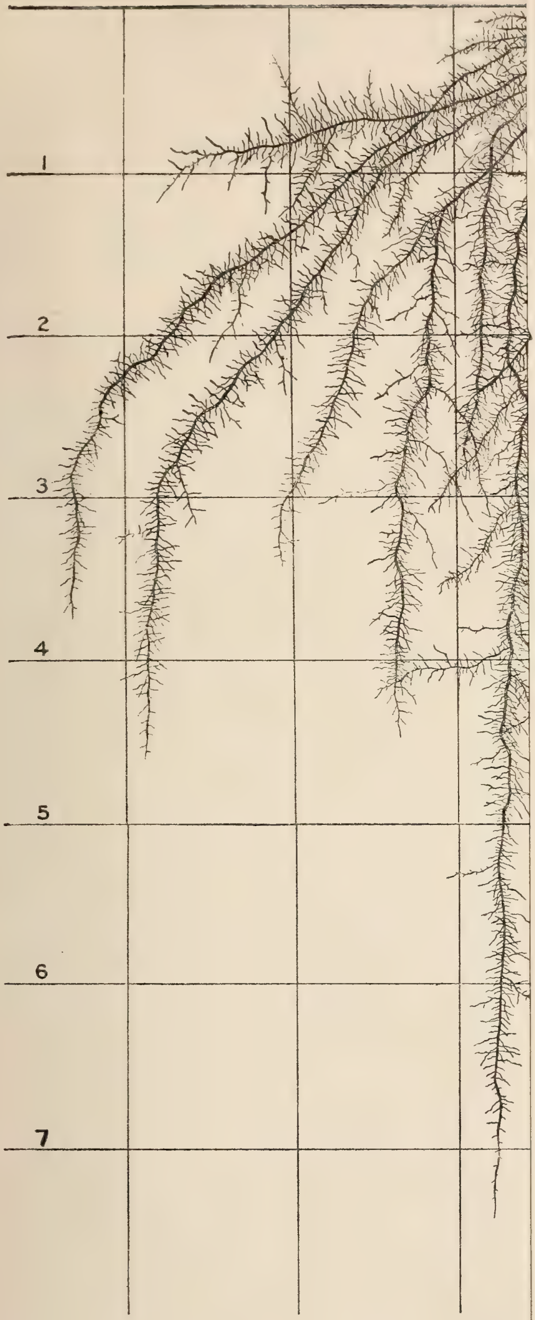


FIG.

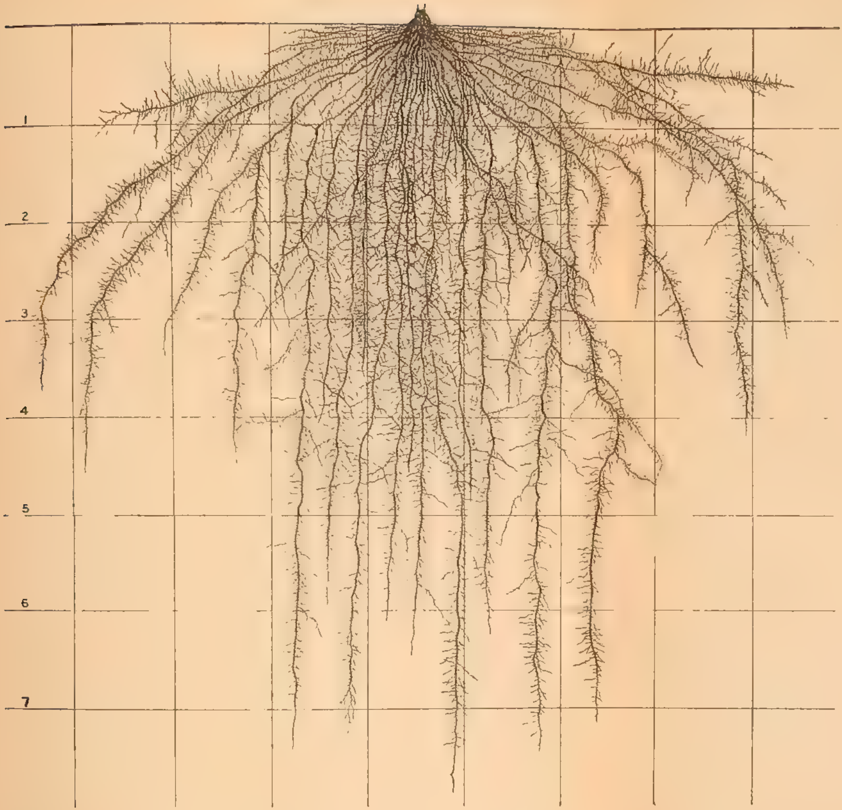


FIG. 9.—Root system of corn on September 2.

a factor in causing the crop to mature somewhat prematurely and resulted in a heavy reduction in yield. The plat averaged only 37 bushels per acre.

Summarizing, the shallower part of the root system was extensive and completed its development early, so far as lateral spread is concerned. The group of roots which penetrated deeper developed later and continued to increase in number and extent practically until the time of maturity. The lateral spread on all sides of the plant was approximately 4 feet and the maximum penetration was 8.2 feet. Thus, corn is furnished with a remarkably extensive and efficient root system.

Earlier Investigations of Corn.

With a few exceptions, most of the investigations of corn roots have been carried on in connection with tillage experiments. Sturtevant (1882) traced corn roots at the New York Agricultural Experiment Station to a depth of 2.5 feet. He states that corn plants for that year produced 1,000 roots in the first 4 inches of soil to 1 root produced below that depth. Beckwith (1885) working at the same station, found that the lateral roots reached a distance of 3.7 feet on all sides of the plant, and that, while a few roots were traced to a depth of 2.5 feet, the majority of them reached a depth not greater than 1.4 feet. Goff (1887) covered the fertile soil in which corn was growing with a 12-inch layer of infertile soil. The corn roots grew horizontally at the upper surface of the fertile soil, but did not penetrate upward into the layer of infertile soil. From this he decided that "abundant food and moisture are more essential to the development of corn than a high soil temperature." Hickman (1887) stated that corn grown in a stiff clay loam in Pennsylvania "seemed to be a shallow rooted plant." He further observed that "nodal roots, especially those later formed, branched out horizontally from the stem for a considerable distance and then turned down quite rapidly." Hays in 1888, working at St. Paul, Minnesota, got results which indicated that corn roots, under his conditions, grow mainly near the surface if there is a good supply of moisture in these layers, but in time of drought they tended to grow deeper and extend shorter distances horizontally. The same investigator (1889), by excavating the roots of corn planted several feet apart, found that they at first grow horizontally because the surface soil is warm, the upper soil is rich in plant food, and contains an abundance of moisture. He further found, after about the fourth week, that both the primary roots and those from the nodes as well take a downward course, the latter from their very beginning. This investigation was carried on in a rather dry season in "drift" soil only fairly retentive of moisture.

King (1892) at Madison, Wisconsin, found that corn roots grow 4 feet deep and in well-drained soil exceed this depth, and also stated that at tasseling time "the roots have fully occupied the upper 3 feet of soil in the entire field." Ten Eyck (1904), by washing out the roots of Kansas Sunflower corn 60 days after planting, at Manhattan, Kansas, found the soil to be filled with roots to a depth of 2.5 feet, while some reached a depth of over 3 feet. He further observed that there were two classes of roots found, namely, "those that curve out from the crown and strike more or less directly downward into the soil" and "those that spread out from the root-stem in a horizontal plane," then "curve more or less abruptly downward, often ending

2 to 3 feet beneath the opposite hill." The corn in this case was level-planted. In examining the mature corn 125 days after planting, the stalks were 8 feet high, the roots "had reached a depth of fully 4 feet, and some were traced to the depth of 5 feet." Shepperd (1905), at Fargo, North Dakota, concluded that "corn roots commonly reached a depth of 3.5 to 4 feet, as is shown by root experiments covering a period of 5 years." Miller (1916) grew Pride of Saline corn at Garden City, Kansas, in sandy-loam soil, irrigated in the fall with 8 to 10 inches of water after plowing. The corn grew in alternate rows with Blackhull kafir and Dwarf milo respectively. The roots were excavated by washing. During the wet season of 1915 they were found to penetrate 6 feet deep and to have a lateral spread of 3.7 feet from the base of the plant. During the dry season of 1914, when but approximately one-third as much precipitation occurred during the growing-period of the plants, the depth of penetration was the same, but the horizontal spread was 8 inches less. The tops reached a height of 7 feet in 1915, but in 1914 they did not exceed 6 feet.

Investigations of corn roots in the United States have been rather limited in extent. In most cases, too, they are somewhat unsatisfactory in regard to the conclusions reached. In fact, except for the work of Miller, this review shows no results in respect to the lateral spread and depth of root penetration comparable to those obtained at Peru.

Other investigators give data on root extent that are greatly at variance with those found in our studies. These discrepancies may be due in part to varietal and environmental differences, but it is also probable that they may also be attributed in part to incomplete and faulty methods of excavation. Indeed, some of the workers state frankly that the roots were badly broken in the process of separating them from the soil by washing and also in some cases that the roots were not traced to their extremities.

With reference to the order of root development, our observations coincide very closely with those of Hays, namely, that the first roots grow horizontally and that later both these primary roots and those from the nodes as well take a downward course, the latter from the very beginning. He stated that this change in direction of growth began about the fourth week. At Peru, however, it came later. Even 5 weeks after planting there was no indication of this downward course on the part of the roots. Moreover, the lateral roots had not yet reached the limit of their spread by approximately 2 feet. Hickman and Ten Eyck also noted the later downward turn of the horizontal roots.

Potato, Solanum tuberosum.

The plat in which the potatoes were grown was plowed April 4 to a depth of 6 inches and immediately harrowed. The next day the ground was furrowed out with a plow into rows 3 feet apart and planted. In preparing the cuttings the tubers of Early Ohio potatoes were cut so that each piece had from two to three buds, and then all the buds but one in each piece were excised. In this way each hill had but one plant. The pieces of tubers were placed 2 feet apart in the row and were covered to a depth of 3 inches. On May 5 the potatoes, which were just coming through the ground, were harrowed to level the surface and kill the weeds. On May 31 and again on June 16 they were hoed with a garden hoe. Each hoeing was shallow in order to kill the weeds but not to disturb the potato roots lying near the surface.

The potato was examined only twice. The first examination was made May 31, 56 days after planting. The tops were 9 to 12 inches high. At this time the root system was almost entirely near the surface. As many as 55 roots took their origin from the base of a single plant and ran off practically parallel to the surface of the soil. They varied from a few inches to 2.2 feet in length. None penetrated deeper than 1.5 feet and with few exceptions were throughout their length within the first 8 inches of soil. The earth about the plants was so thoroughly filled with these roots that it was found impossible to represent all of them in one plane. Consequently the drawing (fig. 10) shows but one-half of the entire root system.

Some of the roots were confined to the first 2 inches of soil. As is shown in figure 10, a number of the deeper roots had a tendency to turn quite abruptly downward. A dry period of short duration occurred at this time, and

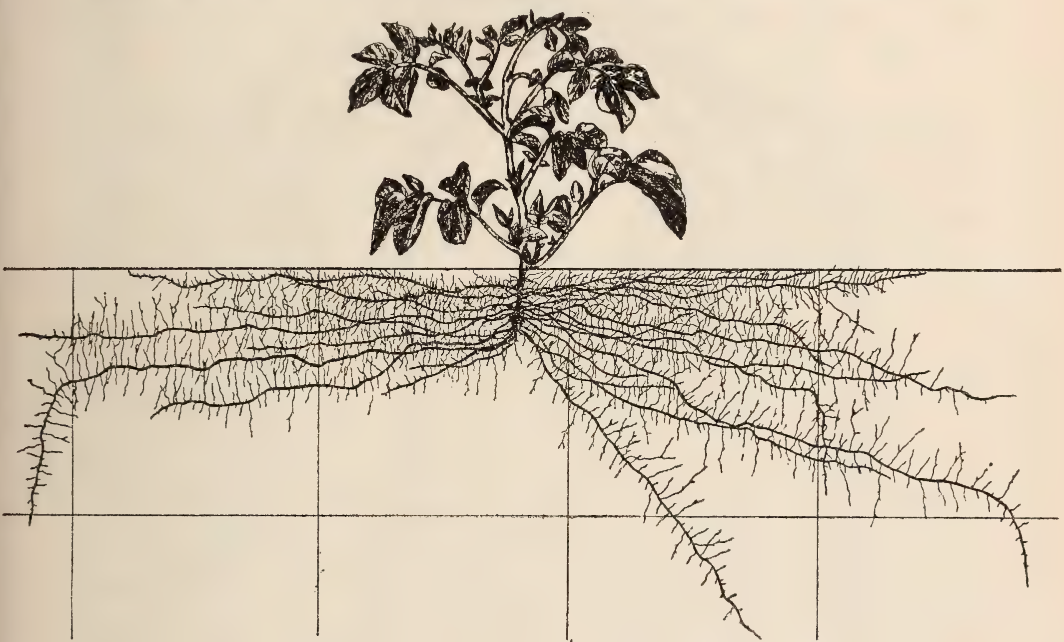


Fig. 10.—One-half of root system of a potato plant 56 days old.

it was uncertain whether this downward turn was normal or whether it was a response to low water-content of the surface soil. The dry weather may have had some influence, but subsequent investigation indicated conclusively that this habit of growth is normal. The main roots were densely covered with thread-like branches from a few millimeters to 3 or 4 inches in length. So numerous were these capillary branches that the soil to the very surface was thoroughly penetrated by them. Several young potatoes from 0.3 to 2 cm. in diameter had formed.

This period, excepting the last part of May, had been rather unfavorable for growth, because of cool weather. The soil-temperature to a depth of 2 feet averaged but 55.1° F. This was due in part to the high water-content of the soil resulting from the heavy April precipitation. At no time, within

the layer occupied by the roots, did the available moisture fall below 11 per cent. Beginning with April 21, when the atmometers were installed, the daily evaporation averaged but 18 c. c. per day. During the last days of May, however, more favorable growth conditions ensued, and the plants passed into the next period under circumstances conducive to rapid development.

The final examination was made on July 8, 94 days after planting, when growth was complete and about one-third of the leaves were dead (plate 1 B). One-half of the mature root system is shown in figure 11. The root system was very unlike those of the cereals, in that there was an almost entire absence of roots penetrating vertically downward from the base of the plant.

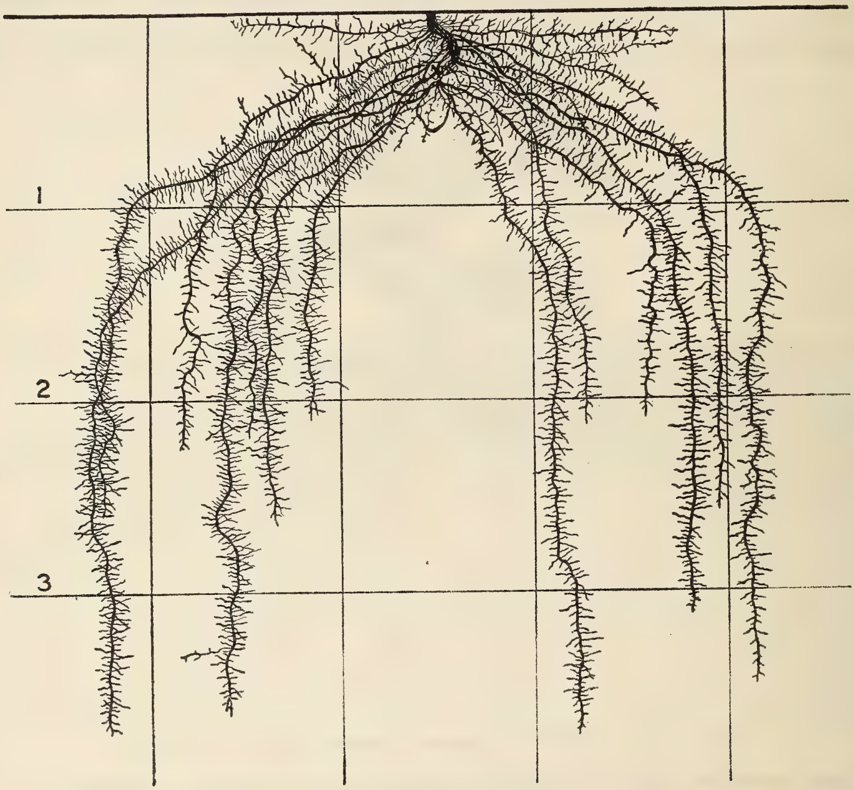


FIG. 11.—One-half of root system of a mature potato plant.

In form it was almost identical with that found in the earlier stage of its development. Practically the only difference was in its extent. With a few exceptions, the roots extended outward and downward until they reached a distance of 0.5 to 2.1 feet from the vertical and a depth of 0.7 to 1 foot from the surface. They then turned more or less abruptly downward and continued their irregular course to a depth of 2 to 4.7 feet. A few roots extended out almost horizontally at a depth of 2 or 3 inches to a maximum distance of 15 to 20 inches, but did not turn downward at that point. All these roots, including both the shallow and deep ones, were freely branched throughout their course, even to their very tips, with fine white branches

from 0.5 to 4 inches in length. Infrequently, longer branches were found near the surface, which sometimes had an extent of 1.3 feet. All of the laterals were frequently rebranched. It should be noted in this connection that the individual plants were quite variable, both in respect to the size of the tops and the number and extent of the roots.

This period was rather warm, with a slight excess of cloudiness and humidity. The mean daily temperature was 75° F. and the average daily evaporation 23 c. c. The rainfall for June, although nearly normal in amount, was not well distributed, over half of it falling during the first four days of the month. However, the plants did not lack water. On June 28 the available moisture to a depth of 5 feet was 11 per cent. The plants did not recover entirely from the retardation in growth which they underwent during the dry, cold month of May. This resulted in a yield of only 2 or 3 tubers per plant, and these were of small size, averaging not over 2 or 3 inches in diameter. The whole plat yielded at the rate of only 32 bushels per acre.

In its early growth the potato had a distinctly superficial system of roots. After extending out horizontally to a distance of 1 to 2.2 feet or more, these same roots then turned more or less abruptly downward and formed the deeper penetrating portion of the system also. This left the subsoil area directly below the plant practically free from its own roots. The individual plants were more variable, both in respect to the size of the top and the number and extent of the roots than were any of the monocotyledonous crops.

Earlier Investigations of Potatoes.

Few investigations on the root development of potato are found in a survey of the literature. Beckwith (1885) reported that at the New York Experiment Station roots of the White Star potato reached a maximum depth of 1.6 feet and that the horizontal roots were traced to a distance of 2.2 to 2.5 feet from the base of the plant. He concluded that most of the roots lay within the first 1.2 feet of soil. Ten Eyck (1899) at Fargo, North Dakota, working with Early Ohio potatoes, stated that the roots during 1898 were few in number and did not penetrate deeply. He washed the roots out of the soil with a jet of water on September 13, at a time when they were partly decayed and, as he states, they made a "bad mess." In 1899 he examined the Rural New Yorker No. 2 potato at the same station and concluded that late-maturing potatoes, of which this variety is an example, "root more freely and more deeply than early potatoes." In this instance he found that the roots reached a depth of 3 feet and that the lateral roots were interlaced between the hills, which were 3 feet apart. He stated that the roots were very tender and were badly broken by washing. In 1900 he again investigated the roots of Early Ohio potatoes at Fargo and found that 43 days after planting they lay for the most part within the first 8 inches of soil. A few penetrated to a depth of 1.5 feet and some of the horizontal ones reached a length of 2 feet. Few fibrous roots were found. At maturity the roots had penetrated to a depth of 2.5 feet. Rotmistrov (1909), working at Odessa, Russia, stated that the potato, unlike most dicotyledons, has many main roots, and again at the same station (1914) concluded that the root systems of potatoes are very short, being approximately 2 feet.

A comparison of these results with those obtained at Peru shows a much more extensive root development at the latter station. At the New York Experiment Station only was the lateral spread as great, while in no case was the depth of penetration so pronounced. These differences may be due in part to the variety of potato grown, and to variations in environmental conditions both climatic and edaphic. It seems, however, that, at least in some cases, the method of excavation was faulty, in that the entire root system was not recovered. In most cases the roots were washed out, and the fragile younger and finer parts largely destroyed. In some instances, too, it seems clear that the block of earth prepared for washing was not extensive enough to include all of the roots.

Comparison of Root Systems.

The most obvious conclusion from a consideration of the data is that these crop plants, like the prairie species that preceded them, are provided with well-developed, deep-seated, and extensive root system (*cf.* Weaver, 1919, 1920). All of the cereal crops examined are similar in having two more or less distinct parts of the root system as regards position. One group of roots in each case spread out horizontally in all directions from the base of the plant and had for its main function absorption from the shallower stratum of soil. In most instances these lay within a foot of the soil surface. The other group of roots, which completed the underground part of each plant, pursued a more or less vertically downward course and penetrated deeply. The potato also had a shallower and a deeper portion of its root system. However, in the development of the potato this end is accomplished in a different manner. Instead of having two more or less different groups of roots, as in the cereals, the same group served both purposes. This was brought about by developing at first a copiously branched, shallow, horizontal group of roots. Later, by turning rather abruptly downward and continuing their course into the subsoil, these also became the deeply penetrating ones. In time of development of these two portions of the absorbing system, the plants fall naturally into two groups; the small cereals forming one group, and corn and potatoes comprising the other. In the former group both the shallow and the deeper penetrating portions began to form more or less simultaneously in the earlier stages of growth. In the latter the shallow system had developed to a rather marked degree before the deeper penetration of the soil began. However, both groups agreed fairly well in that the shallow roots had practically reached the limit of their horizontal spread by the time the tops were in the intermediate stages of growth. Conversely, the longer roots continued to penetrate deeper until the plants were almost if not indeed entirely mature.

All the root systems, as might be expected considering their fibrous character, were well supplied with small branches. But in this particular an examination of the figures shows that the corn and potato were much more abundantly furnished with branches than were any of the others. A comparison of the relative development of tops and roots shows the greater extent of the underground parts in every case except that of corn. They regularly penetrated to a depth at least twice as great as the height of the tops. Indeed, in some instances, especially among the smaller cereals, the

root extent was even much greater. In regard to corn, height growth and root depth were about equal. However, what the corn lacked in relative depth was adequately compensated for by widely penetrating and exceedingly well branched roots. A comparison of the seedling stages of wheat and oats shows that the roots of the former spread more widely. At this stage of development the wheat roots were lighter in color, tougher, and, although abundantly supplied with root-hairs, they did not occur in such density as on the oats. The surface roots of wheat, when compared with those of oats and barley, are found to be both less numerous and extensive. Thus, the ability of oats to more thoroughly exhaust the surface soil of water and nutrients, a belief current among agriculturalists, may have some foundation in fact. Root habit gives a clue to the cause of this phenomenon.

Table 1 gives a summary of the development of the several crops at various stages of growth and affords an easy basis for comparison.

TABLE 1.—*Development of crops at Peru, Nebraska, 1919.*

Crop.	Age of plants.	Average height.	Stage of development.	Maximum depth.	Maximum lateral spread.	Remarks.
	days.	*feet.*		*feet.*	*feet.*	
Oats, University No. 21.	18	0.2	1 leaf	0.7	0.4	3 or 4 roots.
	59	1.1	5 or 6 leaves	3.6	1.0	1 or 2 tillers.
	92	3.0	About half-ripe	6.7	1.4	1 or 2 tillers headed.
Oats, Swedish Select	19	0.2	1 leaf	0.8	0.4	3 or 4 roots.
	60	1.0	5 or 6 leaves	3.7	0.8	1 to 3 tillers.
	93	3.0	Stiff-dough stage	6.8	1.3	1 or 2 tillers headed.
Wheat, Durum	19	0.3	1 leaf	0.7	0.4	4 or 5 roots.
	60	0.8	5 leaves	4.5	1.3	1 to 3 tillers.
	95	2.5	Stiff-dough stage	7.4	1.2	1 tiller headed.
Wheat, Marquis	20	0.2	Second leaf unfolding.	0.9	0.6	3 to 5 roots.
	70	1.7	5 leaves, jointing	5.8	1.3	1 to 3 tillers.
	93	2.7	Stiff-dough stage	6.7	1.3	1 tiller headed.
Barley, Manchuria	20	0.4	Second leaf unfolding.	1.2	0.7	5 to 7 roots.
	54	0.9	5 leaves	4.5	1.3	1 to 3 tillers.
	84	2.3	Stiff-dough stage	6.3	1.3	1 or 2 tillers headed.
Corn, Iowa Silver Mine.	36	1.0	7 or 8 leaves	1.3	2.6	12 to 15 roots.
	57	4.0	4 or 5 joints	4.7	4.0	Plants growing vigorously.
	116	8.5	Husks drying	8.2	4.0	Greater part of leaves green.
Potatoes, Early Ohio	56	0.9	Tubers appearing	1.5	2.2	As many as 55 roots.
	94	2.3	One-third leaves dead.	4.7	2.1	Roots variable in number and extent.

Some preliminary examinations were made of the development of roots and above-ground parts of crop plants when grown as isolated individuals. In general, both were found, in every case, to be more extensive than where the crops were grown under the competition of normal field conditions (*cf.* Weaver, 1920).

Environmental Conditions of Growth.

To understand the causes of such remarkable root development, it will be necessary to consider somewhat in detail the environmental conditions under which the crops grew.

The mellow silt-loam soil, underlaid at a depth of 1 to 1.5 feet with loess of very loose texture, not only absorbs water readily, but has a high water-holding capacity. This ranges from 57 to 64 per cent and is rather uniform to a depth of at least 4 feet, the same type of subsoil extending to depths of many feet. The mechanical analyses of these soils (table 2) shows that they are approximately one-half silt, while the remainder is almost entirely composed of very fine sand and clay.

Table 2.—*Mechanical analyses of soils from Peru.*

Depth of sample.	Coarse gravel.	Fine gravel.	Coarse sand.	Medium sand.	Fine sand.	Very fine sand.	Silt.	Clay.	Hygroscopic coefficient.
feet.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
0.0 to 0.5	0.0	0.0	0.0	0.3	1.8	32.0	46.2	19.7	8.9
0.5 to 1.0	0.0	0.0	0.4	0.7	1.0	27.9	50.6	19.4	9.1
1 to 2	0.0	0.0	0.1	0.2	1.8	27.7	50.1	20.1	8.9
2 to 3	0.0	0.0	0.1	0.4	1.8	26.9	54.6	16.2	8.8
3 to 4	0.0	0.0	0.0	0.1	0.4	33.5	55.3	10.7	9.2

The chemical analyses are given in table 3. According to the Truog test, the soils were slightly acid. The volatile matter and nitrogen are not low, while the other critical elements are present in sufficient quantities to assure good yields.

Table 3.—*Chemical analyses of soils from Peru.*[1]

Depth of sample.	Acidity.	Volatile matter.	Phosphorus pentoxide.	Sulphur trioxide.	Potassium oxide.	Nitrogen.
feet.		*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
0.0 to 0.5	Slight	4.72	0.308	0.006	1.91	0.178
0.5 to 1.0	Do.	4.59	0.308	0.005	2.02	0.164
1 to 2	Do.	4.88	0.267	0.004	2.21	0.139
2 to 3	Do.	3.59	0.296	0.003	1.93	0.084
3 to 4	Very slight.	2.77	0.173	0.015	1.98	0.048

[1] Phosphorus determinations were made by digestion with HNO_3 and HF; sulphur by fusion with Na_2O_2; potassium by fusion with calcium carbonate; and nitrogen by the modified Gunning method.

As pointed out elsewhere, (Weaver, 1920 : 100) the chief limiting factor to crop production in the grassland area west of the Missouri is soil-moisture. In general, it may be stated that in eastern Nebraska most of the precipitation falls during the growing-season and less than one-tenth of it during the three winter months. About half of the rainfall of May, June, and July is from rains of an inch or more in 24 hours. Such a seasonal distribution of moisture is very favorable for the growth of crops. Not infrequently, however, storms occur with a rainfall exceeding 2 inches and occasionally 4 or 5 inches in a period of 24 hours. Such storms invariably result in a high run-off, and they

account largely for the observed deficiencies of moisture for crops in seasons where the recorded rainfall would indicate an abundant supply. The mean annual precipitation at Peru is about 34 inches. In table 4 is given the monthly precipitation from March to August 1919, together with the mean for the five preceding years.

TABLE 4.—*Precipitation in inches.*

Year.	March.	April.	May.	June.	July.	August.	Total.
Mean, 1915 to 1919	1.2	2.7	5.4	4.6	3.2	3.1	20.2
1919	2.0	4.6	1.8	4.3	0.8	1.6	15.1

These data were obtained from the reports of the U. S. Weather Bureau station at Nebraska City, Nebraska, 15 miles north of Peru. March and June were months of rather normal rainfall; April was unusually wet, while May, July, and August had a precipitation far below the average. The only deviation of any importance from these Nebraska City records was July 4 and 5, when two very heavy local showers occurred at Peru. About 2 inches of water fell during a period of 2 hours or less. This resulted in a high run-off. Nevertheless, these showers were very beneficial to the growing crops. However, precipitation is only a very general indicator of conditions for plant growth. Because of differences in time and manner of distribution, amount of run-off, which in turn is influenced by soil structure, rapidity of evaporation, etc., rainfall alone, indeed, yields data of little value in a study of the water relations for crop production. Although it modifies the temperature of both air and soil, and especially the humidity, as well as having a profound effect upon soil aeration, its major influence upon the activities of plants is exerted through its power to replenish soil moisture. The soil may be compared to a great reservoir of water from which growing plants are constantly drawing their supply. When water becomes less abundant in the upper portion of this reservoir, plants must either suffer from lack of water or extend their absorbing organs into the deeper soils. Hence it may be that during this season of drought the roots penetrated somewhat deeper than normally. However, similar results were obtained at this station during 1921, but this was also a year of deficient rainfall. Further studies may show this root habit is quite normal for these rather mellow and relatively well-aerated soils of loose texture, where the subsoil is moist to very great depths. In fact, judging from the root habits of native species, this seems highly probable.

Water-content of the soil, with its effect upon aeration, is the most important factor affecting root development under field conditions. Because of its importance, a rather extensive series of determinations was made. In taking the samples of 100 to 150 grams of soil at various depths, a Briggs geotome was employed. The soil was dried to a constant weight at 105° C. and the water-content calculated in per cent of the dry weight. For convenience, the water in excess of the hygroscopic coefficient is considered available for plant growth. In another place (Weaver, 1920 : 28), it has been pointed out that soil upon which native prairie or short-grasses grow frequently shows a water-content below the wilting coefficient of Briggs and

Shantz (1912), at least to a depth of 4 or 5 feet. On the other hand, during 7 years of field work in many States, the senior writer has never found the water-content to fall below the hygroscopic coefficient, except in the surface soil, where direct evaporation rather than absorption by plants was the cause. These findings are quite in agreement with those of Alway and others (1919). However, it should be made clear that we are not at all certain that crop plants are as efficient in exhausting the water-supply as is native vegetation. Moreover, it may be found that certain plants of either group are more or less efficient than others. The thorough distribution of a minutely branched root system through all parts of the soil, as already described, would promote efficient absorption.

In figure 12 the available water-content of the soil is given to a depth of 3 feet from March 31 to June 16. A glance at this figure shows clearly the

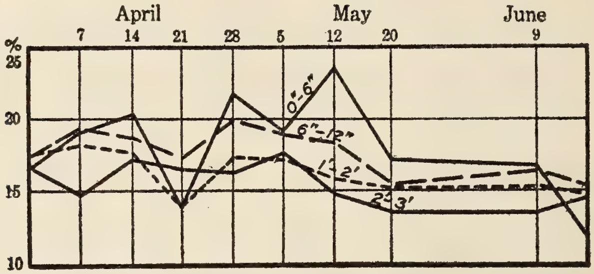


FIG. 12.—Water-content in excess of hygroscopic coefficient from March 31 to June 16.

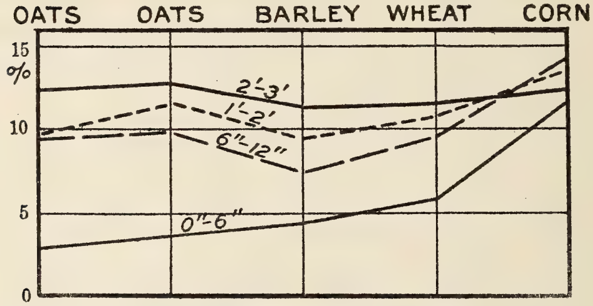


FIG. 13.—Water-content in excess of hygroscopic coefficient in the several crop plats on May 30.

rather uniform distribution of moisture, as well as the fact that practically throughout the entire period a minimum of 14 per cent was available at all levels. Since the hygroscopic coefficients of these soils vary from 8.9 per cent (surface 6 inches) to 9.2 per cent (fourth foot), the actual water-content for the period did not fall below 21 per cent. These data are from an open space 10 feet square in the corn plat. Water losses here were by surface evaporation only. Later in the season the area was occupied in part at least by the widely extending roots of the corn, and further water-content determinations were not made.

The water available to the various crops at the several levels on May 30 is given in figure 13. At this time no marked differences in the water-content

of the several plats are apparent, except that the oat plats were drier in the surface 6 inches, and those of corn showed more available water at all levels to 3 feet than the cereals which were planted earlier. At this time the latter were about 12 inches tall, and, although the main development of roots was in the surface 2 feet of soil, not a few extended into the third foot or beyond (*cf.* figs. 1 A, B and 3 B, C). The younger corn plants had rooted much more superficially, and the total transpiring surface was less extensive than in the smaller cereals at this time. However, from the uniformity of the water-content in the third foot, it seems clear that little absorption had occurred at this level. The water relations of the soils in the several plats on June 23 are shown in figure 14. The small percentage of available water at all levels, when compared with conditions on May 30, is at once evident, and shows clearly that the roots were probably extracting water at depths of at least 3 feet.

It is interesting to compare the water-content of the oat plats with that of wheat and barley. On June 23 the average water-content of the two oat plats was only 70 per cent of the average of the two wheat plats, and 65 per cent of that of the barley plat. Five days later, on June 28, the average water-content of the oat plats was 76 per cent of the average of the wheat plats and 77 per cent of that of the barley plat. In other words, on June 23 the oat plats contained 30 per cent less moisture than the wheat plats and 35 per cent less than the barley. On June 28, the oat plats contained 24 per cent less moisture than the wheat and 23 per cent less than the barley. This agrees well with the root habit. A comparison of the mature root systems (figs. 2, 4, and 6) shows at once that the number of deeply penetrating roots of oats is 1 or 2 greater per plant than that of wheat and 3 or 4 greater than that of barley. It is also possible that oat roots are more efficient absorbers than those of wheat and barley.

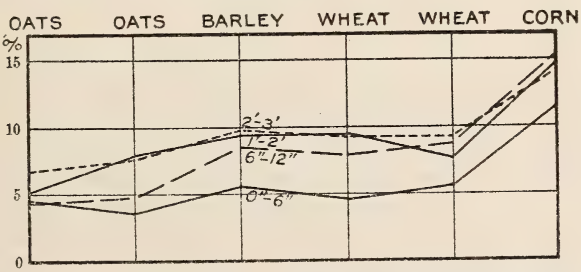


FIG. 14.—Water-content in excess of hygroscopic coefficient in the several plats on June 23.

The relative available water-contents of the potato and corn plats are also significant. On June 28, at practically every level represented, the potatoes had exhausted the soil-moisture more completely than had the corn (table 5). The average of all depths gave 10 per cent less in the potato plat. But 9 days later, on July 7, the corn, responding to the ideal growing weather by a very rapid development of the top, had reversed these conditions, for the corn plat now had approximately 10 per cent less moisture than the potato plat. A week later, July 15, this difference had increased to 19 per cent. Another factor occurring during this two-week period may have had some

influence on the water-content relations. The potato leaves had begun to wither and die. However, it seems probable that the rapid development of the aerial parts of the corn was the major cause of decreased water-content.

TABLE 5.—*Water-content in excess of hygroscopic coefficient in the corn and potato plats.*

Depth in feet.	June 28.		July 7.		July 15.	
	Potato.	Corn.	Potato.	Corn.	Potato.	Corn.
0.0 to 0.5	10.3	10.4	14.7	14.0	9.4	7.3
0.5 to 1	8.5	11.9	17.9	15.6	14.2	10.1
1 to 2	11.7	11.3	15.4	13.3	13.0	11.5
2 to 3	10.8	12.2	13.4	12.8	13.1	11.5
3 to 4	11.9	12.1	....	....	....	....
4 to 5	11.1	13.6	....	....	....	....

An examination of table 6 shows how efficient is the massive, deeply penetrating root system of corn. During the dry month of August the available moisture had been reduced to only 4 or 5 per cent, even to a depth of 5 feet.

TABLE 6.—*Water-content in excess of the hygroscopic coefficient in the corn plat.*

Depth in feet.	July 22.	July 29.	Aug. 5.	Aug. 12.	Aug. 20.	Aug. 25.	Sept. 2.
0.0 to 0.5	2.7	0.1	20.8	2.0	1.5	4.0	1.5
0.5 to 1	5.5	2.6	2.9	7.9	5.4	4.9	4.3
1 to 2	8.4	7.2	4.4	8.5	6.1	4.9	5.1
2 to 3	10.9	6.1	4.2	8.2	5.6	6.0	3.9
3 to 4	...	11.1	...	...	...	...	2.9
4 to 5	...	13.1	...	...	...	...	3.4

The enormous transpiring surface presented by a field of corn should be emphasized. Kiesselbach (1916) has calculated that an acre of corn in eastern Nebraska planted in hills 3.5 feet apart with 3 plants per hill has a transpiring surface of approximately 4 acres. Closely correlated with the development of the transpiring area is the growth of the absorbing system. Figures 8 and 9 well illustrate the enormous absorbing area of a single stalk, while table 6 indicates the degree to which this cereal exhausts the available moisture even to a depth of 5 feet.

Soil temperature is an important ecological factor affecting root growth. Like soil aeration, it affects the development of the root system not only directly, but also plays a part in the life activities of soil micro-organisms. These may affect the plants directly or alter the chemical composition of the soil and thus influence the root environment, which in turn may modify its development. The importance of temperature in the development of root systems has only recently been emphasized (Cannon, 1918), and comparatively few investigations have been made on the evaluation of this factor in root growth. An examination of figure 15, which gives thermometer readings at various depths, shows at once that the temperature of the wet

soil was quite too low for maximum root development during the cold rainy month of April (*cf.* Lehenbauer, 1914). During May, a slow but uniform rise occurred, while differences between the temperatures on June 9 and 23 were quite pronounced. This ushered in a hot, dry period which extended to July 4. It is interesting to note that the deeper soils into which the new roots were extending were progressively colder. Undoubtedly temperature has a marked influence upon crop-root development under field conditions.

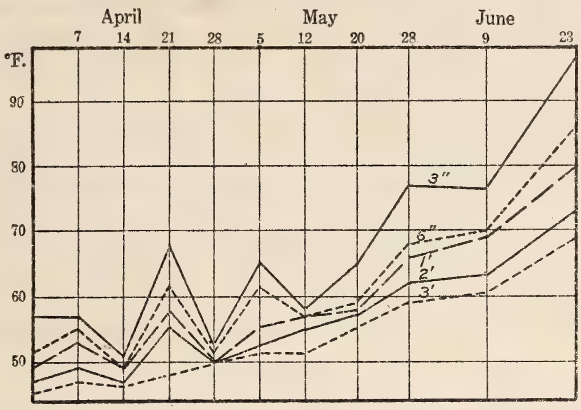


Fig. 15.—Soil-temperatures at various depths during 1919.

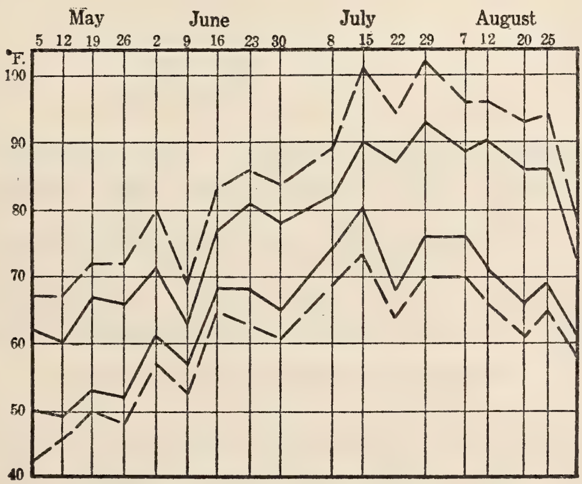


Fig. 16.—Average day and night temperatures (solid lines) and average maximum and minimum temperatures.

Indeed, it has been suggested (Shepperd, 1905) that in northern latitudes, where the ground freezes deep in the winter, the soil may be too cold for the roots of cereals to penetrate to a depth greater than 3 feet before midsummer (*cf.* Pulling, 1918).

The average weekly day and night temperatures are shown in figure 16, which also includes the average weekly maximum and minimum temperatures. The average for the day temperatures was determined from the

weekly record-sheets of the thermographs by adding the temperatures beginning at 8 a. m. and every 2 hours thereafter until 6 p. m. for each day and dividing the sum by the total number of 2-hour intervals. Those for the night intervals were calculated in a similar manner, beginning at 8 p. m. and including the readings until 6 a. m. The weekly maximum and minimum readings were determined directly by averaging the 7 highest and 7 lowest points respectively, on the weekly record-sheet. This method of evaluating temperatures takes into account both temperature extremes and the element of time. A gradual increase in temperature with the progress of the season is evident. The high temperatures during July and August were very favorable for the rapid development of corn.

The factors of high temperature, low humidity, and wind movement combine to increase the evaporating power of the air and transpiration of crops. In a study of root development it is important to consider the above-ground environment. For just as the possible growth of the aerial parts of plants is affected by the extent of the development of the root system, conversely the environmental conditions to which the aerial parts are subjected, especially as concerns their water relations, must reflect themselves in root development. Table 7 shows the average daily evaporation losses during the

TABLE 7.—*Average daily evaporation at Peru, 1919.*

	c.c.		c.c.
Apr. 21 to 28	5.8	June 16 to 23	27.3
Apr. 28 to May 7	11.8	June 23 to 30	26.6
May 7 to 12	20.0	June 30 to July 8	20.9
May 12 to 20	24.0	July 8 to 15	27.0
May 20 to 28	28.3	July 15 to 22	22.7
May 28 to June 9	19.0	July 22 to 29	44.1
June 9 to 16	21.4	July 29 to Aug. 5	38.4

several periods from April 21 to August 5. An examination of these data reveals no unusually high evaporation rates when compared with other seasons[1] (Weaver 1919, 1920), except during the latter part of July and early in August. At this time all of the crops except corn were ripe. During the remainder of August only one or two light showers occurred and the temperature most of the time was quite high (fig. 16). These conditions doubtless reflected themselves in the extensive root development of the corn.

SUMMARY OF ROOT DEVELOPMENT.

All the cereals, including corn, possessed a root system in which there was a definite group of more or less horizontal, spreading roots lying within the first 1 to 1.3 feet of soil, and a second group of deeply penetrating roots extending into the subsoil to depths of 6 or 7 feet.

The Early Ohio potato differed from the other plants in that the same group of roots which at the outset formed the shallow portion of the system subsequently became the deeper portion by turning more or less abruptly to the vertical position and growing downward.

In every instance the root systems were very extensive in relation to the size of the top. All the main roots were abundantly supplied with branches

[1] Since these atmometers were not fitted with non-absorbing apparatus, direct comparisons of actual losses can not be made but it is certain losses were higher than the figures indicate.

that greatly increased their absorbing area. This was especially marked in the case of corn and potatoes.

The more superficial roots reached their maximum development first. In most cases this occurred about the time the top had reached an intermediate stage of growth; the deeper roots developed coordinately with the top and thus balanced water absorption and transpiration.

Oats reduced the soil moisture to a greater degree than any of the other small cereals. Corn in its later stages of growth was an extravagant user of water. The potato showed the greatest variation in the number and extent of its roots.

The root systems of isolated crop plants are greatly modified as to nature and extent when compared with similar plants grown under the competitive conditions imposed by the rate of planting in ordinary field practice.

The season in which this investigation was carried on had a deficit of rainfall, particularly during the months of May, July, and August. The deficiency was sufficient to mark it as a dry crop-year.

II. INVESTIGATIONS AT LINCOLN, NEBRASKA, IN 1919 AND 1920.

The root development of crop plants at Lincoln has been studied for the seasons of 1919 and 1920. Data on the root relations of 4 leguminous crops, 4 forage plants, sunflowers, and oats, in both upland and lowland areas, during 1919, have already been published (Weaver, 1920). During 1920, root studies were continued, with particular reference to the successive stages in the development of oats, wheat, barley, alfalfa, and sweet clover and their correlation with environmental factors. In these experiments White Kherson oats, Marquis Spring wheat, and Manchuria barley were grown. The seed of these and also of alfalfa and white sweet clover were obtained from a local seed company.

The cropped areas were the same as those used the preceding year. The upland plats were located about 3 miles north of Lincoln, on a broad, level hilltop. The soil is a silt-loam of fine texture, but much more compact than that at Peru. The lowland station was located about a mile south of the former and on the edge of the flood-plain of Salt Creek, in rich alluvial silt-loam.

Mechanical analyses of the soils are given in table 8, together with the moisture equivalents computed from the mechanical composition by the formula of Alway and Russel (1916 : 842). These data show that both soils are fine-textured, being composed mostly of silt and clay. A study of the table shows that they are remarkably similar.

TABLE 8.—*Mechanical analyses of soils from Lincoln.*

Depth of sample.	Coarse gravel.	Fine gravel.	Coarse sand.	Medium sand.	Fine sand.	Very fine sand.	Silt.	Clay.	Moisture equivalent.
Upland plats:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
0.0 to 0.5 foot......	0.0	0.0	0.3	0.5	1.6	19.8	48.6	29.2	31.4
0.5 to 1.0 foot......	.0	.0	.2	.6	1.3	16.7	52.4	28.8	31.8
1 to 2 feet.........	.0	.0	.1	.2	0.8	16.7	55.6	26.6	31.5
2 to 3 feet.........	.0	.0	.1	.1	0.5	19.0	57.9	22.3	30.1
Lowland plats:									
0.0 to 0.5 foot......	.1	.4	2.2	1.8	5.0	25.0	41.3	24.3	27.7
0.5 to 1.0 foot......	.3	.7	2.1	2.2	5.0	25.4	38.8	25.8	27.9
1 to 2 feet.........	.2	.3	1.3	1.5	3.7	21.4	40.8	31.0	30.6
2 to 3 feet.........	.0	.1	0.4	0.5	1.7	19.2	43.4	34.7	32.9

Table 9 gives the chemical composition of representative composite samples of soil at various depths from the two areas. A study of the table shows that the soils at the two stations are not strikingly different. It may be noted that the lime-content is about the same in both fields. However, the greater amount of volatile matter and the greater nitrogen-content at all depths indicate more favorable conditions for growth in the lowland plats, and this probably accounts in part for the more rapid growth and better development of the crops in this field. The soil in both fields showed medium acidity in the first foot, slight in the second, very slight in the third, while the fourth foot showed no acidity, but was slightly carbonaceous.

Both areas had been cropped for many years. The crop of the preceding year in the upland was Sudan grass; the lowland area had lain fallow. The cereals were sown in alternating strips, 100 feet long and 10 feet wide, with planted discard areas between. On the upland the plats were all in duplicate. The rate of seeding for oats, wheat, and barley was 56, 75, and 60 pounds per acre, respectively. Alfalfa and sweet clover were seeded at the rate of 12 pounds per acre in plats 50 feet long and 10 feet wide.

TABLE 9.—*Chemical analyses of soils by digestion with hydrochloric acid (sp. gr. 1.115) for 120 hours.*

Depth of sample.	Insoluble residue.	Soluble salts.	Volatile matter.	Iron and aluminium oxides.	Calcium oxide.	Magnesium oxide.	Phosphorus pentoxide.	Nitrogen.
Upland plats:	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
0.0 to 0.5 foot	76.87	17.12	6.01	13.20	0.68	1.19	0.13	0.159
0.5 to 1.0 foot	75.70	18.58	5.72	14.25	.70	1.32	.12	.134
1.0 to 2.0 feet	76.17	19.08	4.75	14.72	.75	1.68	.12	.079
2.0 to 3.0 feet	77.86	18.46	3.68	14.03	.86	1.69	.15	.045
Lowland plats:								
0.0 to 0.5 foot	79.34	12.96	7.70	9.57	.68	.75	.13	.218
0.5 to 1.0 foot	79.63	13.66	6.71	10.27	.63	.77	.10	.187
1.0 to 2.0 feet	78.11	15.83	6.06	12.11	.64	1.01	.08	.135
2.0 to 3.0 feet	74.78	19.82	5.40	15.20	.76	1.27	.09	.082

Preparatory to seeding, both fields were plowed to a depth of 5 inches on March 29 and repeatedly harrowed until a good seed-bed was formed. All of the crops on the upland were planted on March 31, while the lowland area, because of winter weather, was not seeded until April 9. At the time of planting both fields were in excellent tilth. The seed was sowed broadcast by hand and hoed in to a depth of 1 to 3 inches. To assure uniform seed distribution, each plat was subdivided into areas only 10 by 25 feet, and the appropriate amount of seed scattered very evenly over each area. After planting, no further attention was given to the cultivation of the crops, except to pull out the larger weeds from the grain fields and keep the plats of legumes clean in a similar manner.

OATS, AVENA SATIVA.

The first examination of root development was made on May 1, in the upland plats, 31 days after planting. The crop was evenly developed, with an average height of 2 inches and a maximum leaf-length of 3 inches. About half of the plants had only one leaf unfolded; on the rest the second leaf varied from a few millimeters to over 2 inches in length. Some of the plants had only 3 roots, but most of them had 5 to 7. The primary roots, or at least one of them, reached a maximum depth of 7 or 8 inches; the younger roots were only 1 to 4 inches in length. The working depth of the roots was about 5 inches. Where the seed had been planted more than 1.5 inches deep, a pair of unbranched roots about 0.3 inch in length had arisen from opposite sides of the node about an inch below the soil surface. On all of the other

roots, laterals from 0.1 to 1 inch in length occurred at the rate of 7 to 15 per inch, except near the root-ends, 0.5 to 2 inches of which were unbranched. All of these laterals were of the first order only (fig. 17). The primary set of roots spread laterally at an angle of about 45 degrees from the vertical; the maximum lateral spread on any side of the plant did not exceed 3 inches.

The slow rate of development was due to adverse growth conditions. In fact, during this period of 31 days, the growth was about equal to that of 18 days at Peru (*cf.* p. 31). Rotmistrov (1909 : 33) found the roots of oats, wheat, and barley had an average depth of 12 inches only 7 days after the appearance of the sprout. He does not record the environmental conditions of the plants. In our experiment the influence of temperature is clearly shown by the fact that oats planted in the same field on May 15 revealed a much more advanced development of both shoot and root 15 days later than had occurred in a month when the seed was sowed on March 31. Thus, the very slow development of oats is clearly correlated with the unfavorable conditions for growth. Throughout the month of April the weather was cold and wet. Excessive cloudiness prevailed and there was a large deficiency in sunshine. The ground was frozen for several days following April 2, and more or less covered with snow from April 2 to 9, while freezing temperatures with light snow occurred during the latter half of the month.

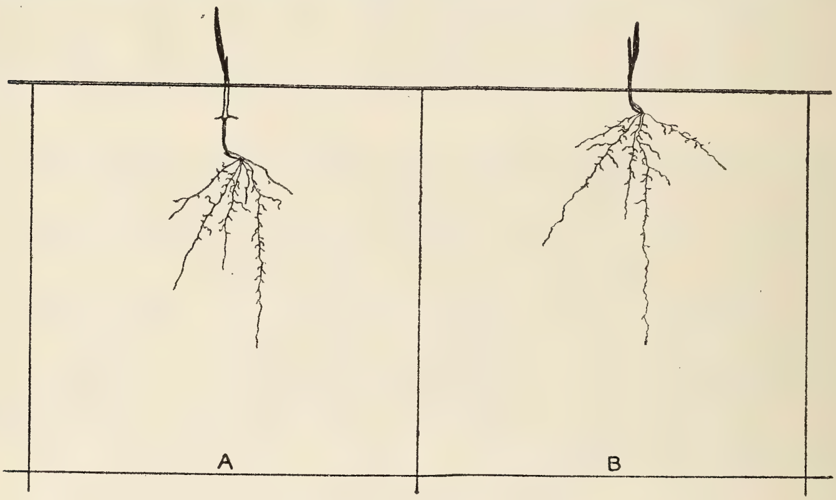


Fig. 17.—A and B. Oats 31 days old.

There were only 6 clear days. The soil was wet and cold. A water-content of about 22 per cent was rather evenly distributed throughout the first 5 feet of soil. Thermograph records from a depth of 6 inches in an adjoining prairie,[1] gave an average temperature of about 47° F. for the last 15 days of April. During this period the minimum soil temperature fell to 42° F., and at no time did the maximum exceed 54° F. On May 5 the soil temperature at depths of 0.5 to 2 feet in the crop plats ranged from 61° to 54° F. respectively.

[1] Thermographs and evaporimeters were installed in native grassland areas adjoining the crop plats at all the stations except Peru, in connection with "Transplant Quadrats and Areas" (see Year Book, Carnegie Institution of Washington, 1920 : 355)

On May 15, when the plants were 45 days old, a second examination was made. They had an average height of about 4 inches and on most of them the fourth leaf was fairly well developed. They had not yet begun to tiller. The number of roots varied from 7 to 14, with an average of about 8. The longer ones penetrated to depths of 1.6 to 2 feet, while the maximum lateral spread did not exceed 0.5 foot. Some of the younger roots were only 1 to 4 inches long and without branches. They extended in a horizontal or oblique direction, the longer ones sometimes being fairly well supplied with short laterals of the first order. On the older roots, branches of the second order, some nearly an inch in length, occurred, but they were not abundant. The

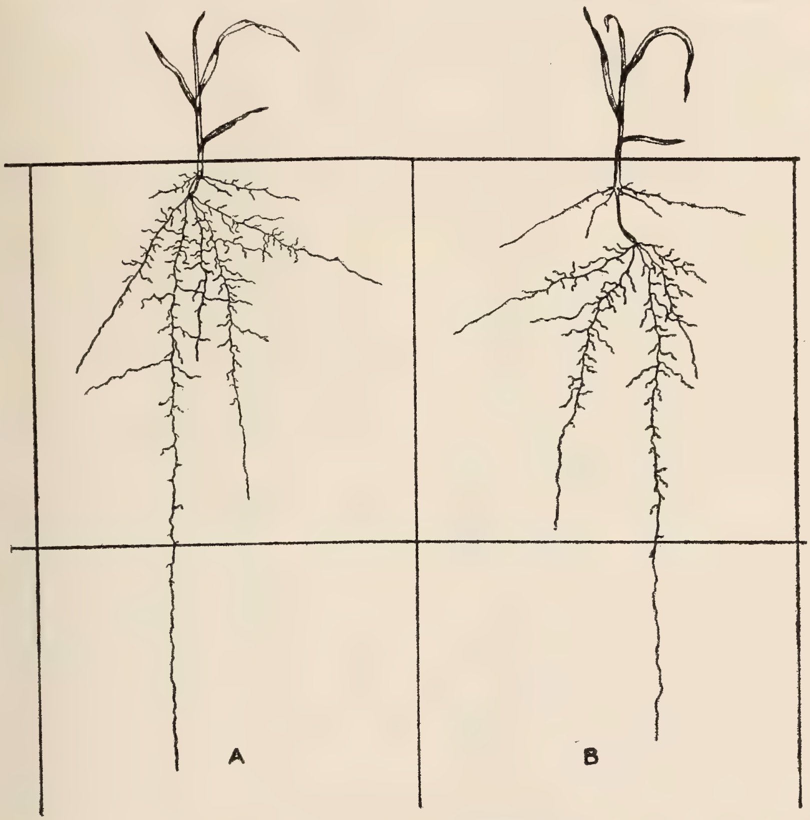


Fig. 18.—A and B. Oats 45 days old.

primary laterals, especially in the surface 8 inches of soil, had reached a length of 1 to 3 inches. Below 8 inches depth, only laterals of the first order were found, and none exceeded 0.8 inch in length, while frequently the last 6 or 8 inches of the glistening white roots were entirely destitute of branches. On seeds that were planted deep, a whorl of 4 to 6 roots had developed an inch below the surface (fig. 18). The root system had a working depth of about 7 or 8 inches. Thus, during this interval of 15 days, although growth conditions were more favorable than before, the plants continued to develop slowly.

The weather for the most part remained cold and cloudy, but no frost occurred. The water-content of the soil averaged about 30 per cent. The soil temperatures remained low (minimum 52°, maximum 66° F., at a depth of 6 inches). Air temperatures, recorded by a hygrothermograph, appropriately sheltered and placed with the recording apparatus 4 inches above the soil surface in an adjacent prairie, gave an average day reading of about 63° F., while the average night temperature was only 53° F. The relative humidity was high.

Rotmistrov (1909 : 34) states that at the end of 21 days after the appearance of the sprout, not only was the extreme breadth of the root system marked off, but the depth of penetration reached 0.5 meter and roots of the third order were clearly visible, the whole forming a felt-like entanglement. Clearly our plants were developing more slowly. However, oats planted May 4, and examined 26 days later, were further developed than 45-day-old plants just described. They were 5 inches high, had 5 leaves each, and some had tillers. The root growth was proportional. It is interesting to note also the more rapid root penetration of White Kherson oats in the loess soils at Peru. Here plants only 14 days older than those just described had extended their roots into the fourth foot of soil.

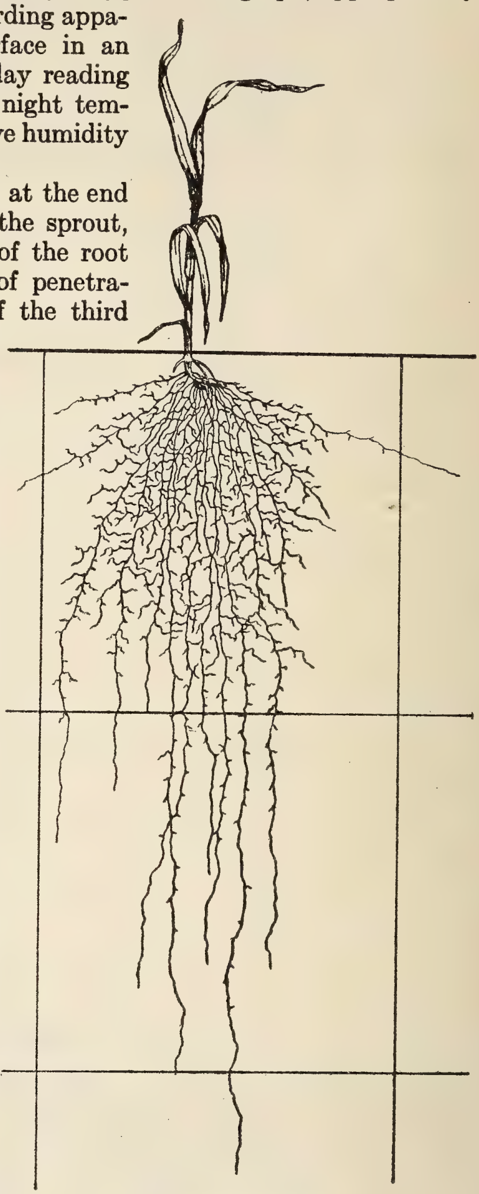


Fig. 19.—Oats 60 days old.

Fifteen days later, on May 30, the root development was again studied. During this period both roots and shoots had grown rapidly. Although the soil remained quite wet (25 to 30 per cent water-content), it was considerably warmer, the average daily temperature during the last week of May reaching 71° F. at a depth of 6 inches. This was higher than the average air-temperature (65° F.) for the same interval. Fewer rains and less cloudy weather occurred during this last half of the month, although the humidity remained high.

The average height of the plants was about 9 inches, but some were 3 inches taller. Each plant had 7 to 9 leaves, one or two of the oldest ones being either dead or rapidly deteriorating. About one-tenth of the plants had

developed one or two tillers. Root counts of a large number of individuals gave a total of 16 to 27 per plant. Several roots were traced to a maximum depth of 2.7 feet, the average maximum depth being about 2.3 feet. The average lateral spread was only 6 inches, although some roots extended horizontally or obliquely away from the plant to a distance of 7 or 8 inches. The working depth had reached the 1.5-foot level. Besides the greater number of primary roots, their wider spread, and deeper penetration, there was a greater development of laterals, both in number, length, and secondary branching. Many of the younger roots near the soil surface spread laterally only 3 or 4 inches; in general, the widest-spreading roots ended in the surface 4 to 8 inches of soil. In the first 8 to 12 inches of soil the abundant laterals sometimes reached a length of 0.2 to 2.5 inches; secondary branches were few and seldom more than 0.3 inch long. At greater depths the branching was much poorer and the laterals shorter, in fact, the last 6 to 12 inches of the thick, straight, white root-ends were devoid of branches (fig. 19).

The fourth examination was made on June 19 and 21, when the plants, now 80 days old, were beginning to blossom. They had an average height of about 2 feet, although some were 4 inches taller. Many of the plants had only 1 stem, others had from 1 to 5 tillers each, while perhaps 2 was an average.

TABLE 10.—*Water-content in excess of hygroscopic coefficient in the crop plats at Lincoln, 1920.*

Date.	0 to 0.5 foot deep.		0.5 to 1 foot deep.		1 to 2 feet deep.		2 to 3 feet deep.		3 to 4 feet deep.	
	Upper.	Lower.	Upper.	Lower.	Upper.	Lower.	Upper.	Lower.	Upper.	Lower.
Mar. 31......	13.0	....	16.1	....	15.2	....	14.1	....	11.3	....
Apr. 10......	18.8	18.7	18.1	19.4	16.0	17.0	16.1	15.1	14.6	14.1
May 4.......	20.9	....	....	....	22.1	....	....	....	....	....
May 15......	20.7	20.5	19.2	21.5	23.9	24.8	....	....	....	....
June 3.......	16.6	....	18.8	....	16.5	....	15.5	....	....	....
June 4.......	....	14.7	....	19.0	....	17.5	....	15.0	....	17.1
June 16......	5.3	13.0	8.3	16.1	12.5	7.6	15.4	12.1	16.6	15.9
June 24......	1.3	1.7	8.5	9.7	9.7	10.1	....	....	....	....
July 14.......	18.7	21.1	13.6	17.5	11.5	10.8	8.0	7.0	14.7	7.1
Aug. 9.......	1.5	0.8	6.0	1.3	6.7	4.0	7.0	5.9	8.2	9.6
Aug. 31......	Continued heavy rains; no samples taken									
Wilting coefficient.......	14.4	14.7	16.0	14.1	14.8	13.6	14.7	16.3	15.2	15.9
Hygroscopic coefficient..	9.8	10.0	10.9	9.6	10.1	9.2	10.0	11.1	10.3	10.8

June was an unusually favorable month for crop growth. 8 to 16 per cent of available water occurred in the 0.5 to 5 foot soil-level, while drought conditions in the surface 0.5 foot were approached only during the latter part of the month, following the interval under consideration and when the grain was ripening (table 10). On June 3, soil temperatures in the oat plats at a depth of 0.5 to 2 feet ranged from 69° to 52° F. The graphs of soil and air temperatures, as well as that of humidity, indicate favorable growth conditions (fig. 20). Throughout the period the evaporation rate averaged about 20 c. c. per day (table 11).

TABLE 11.—*Average daily evaporation,*[1] *at Lincoln, 1920.*

	c.c.		c.c.
May 5 to 12	10.5	June 30 to July 7	13.2
May 12 to 19	14.9	July 7 to 14	13.8
May 19 to 26	13.5	July 14 to 21	19.1
May 26 to June 2	15.8	July 21 to 28	18.7
June 2 to 9	15.9	July 28 to Aug. 5	19.3
June 9 to 16	25.6	Aug. 5 to 12	20.7
June 16 to 23	11.3	Aug. 12 to 19	16.3
June 23 to 30	19.5	Aug. 19 to 28	9.6

[1]All atmometers, exept those at Peru, were equipped with the non-absorbing device.

The roots had attained a maximum lateral spread of 0.8 foot, and a working depth of 2.3 feet, while a few reached a maximum depth of 4.1 feet. A comparison of figures 19 and 21 A shows that the chief difference between the older root system and the younger, aside from greater length growth of most of the roots, is one of increase in number and branching of laterals. In fact, at the early stage (May 30), the general area to be occupied by the mature root system was well blocked out. Later it had been increased some-

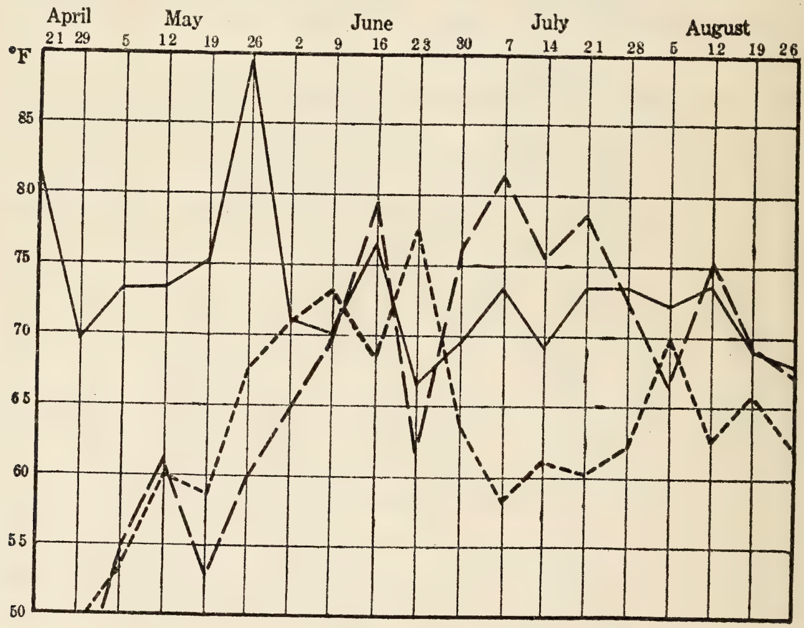


FIG. 20.—Average daily air-temperature (long broken lines), soil-temperature (short broken lines), and humidity (solid line), 1920.

what in width and considerably in depth, but especially it had come to be occupied much more thoroughly in all parts by a fine network of delicate roots. In the surface foot of soil, 7 to 10 laterals, and sometimes as many as 15 to 18, occurred on a single linear inch. On the scale to which the drawings were made it was very difficult to show all of the multitude of rootlets. The laterals were mostly 1 to 2 inches long, infrequently 3 to 5 inches, and were furnished only poorly with secondary branches. Branchlets of the


A
B
1
1

FIG. 21.—A. Oats at time of blossoming. B. Wheat at time of blossoming.

third order were rare. In the second foot the branches became shorter, and not infrequently, for considerable distances, none were over 0.1 to 0.2 inch in length. Below 2.3 to 2.5 feet the number of roots decreased rapidly. While many of them were very poorly branched and often gave rise to only a few rootlets 0.1 to 0.5 inch long, in the course of several inches, most of them were branched quite regularly at the rate of 5 or 6 laterals per linear inch. These unbranched rootlets varied from 0.5 to over an inch in length.

At this time a comparison was made with the development of oats in the lower crop plats. Due to a more fertile soil, as well as a more constant and greater supply of available water in the surface 0.5 foot (12 to 15 per cent), the crop was better developed (*cf.* tables 9 and 10). The plants which were beginning to blossom were 2.6 feet in average height, although some exceeded this by 0.5 foot. They had tillered more freely than the plants in the upland and the stand was thicker. The poorer stand and growth in the upland plats was probably due to the earlier planting and to differences in soil fertility and water-content.

In the lowland area the maximum root depth (3.7 feet) was somewhat less than on the upland, although the working depth (2.7 feet) was greater. Little difference was determined in degree of branching or in lateral spread.

The relatively slower development of the 1920 crop as compared with that of the more favorable growing-season of 1919 stands out strikingly. On June 12, 1919, 49 days after oats were planted, the crop in the upland area was 1.3 feet tall and had a working depth of 2.1 feet and a maximum depth of 2.8 feet. At the lowland station plants 1.8 feet high had roots with a working depth of 2.3 feet and a maximum depth of 3.3 feet (Weaver, 1920 : 134). Thus plants only 49 days old, during this more favorable season, while not developed as far as the 80-day-old plants just described, were far beyond the latter at the age of 60 days.

A final examination was made a few days after harvesting the crop on July 12. At this time the roots, except the deeper ones, were quite brittle and the cortex greatly shrunken, indicating that much material had been removed upward during ripening. Otherwise, the differences in the mature root system from that described at the beginning of the blossoming period are a somewhat greater working depth (2.7 to 2.8 feet) and an even more thorough occupation of the soil-mass already delimited at the earlier examination.

The period June 20 to July 12 was one very favorable for root growth. Several well-distributed rains furnished an abundant water-supply to the surface soils, while the deeper layers had 8 to 16 per cent of water constantly available. On the lower crop-plats, moisture conditions were also favorable (table 10). Here the roots of the matured plants had penetrated to maximum depths of 4.3 to 4.8 feet, but the working level (2.8 feet) had changed little since the previous examination 24 days earlier. Allowing for differences in soil condition (although all root excavations in any plat were made within a radius of a few meters), these findings agree only in part with those of Rotmistrov (1914 : 24) that "towards the commencement of flowering the development of the root system finishes, or the growth of the roots after that to the attainment of maturity is insignificant."

The grain yield of the crop-plats was not determined. 20 or 30 quadrats were selected from each plat (Kiesselbach, 1918), and the total dry weight of tops, including grain, obtained (*cf.* p. 76).

The extent of shoot and root of the oats in both upland and lowland areas during 1919 was almost identical with that of 1920, although the crop in 1919 reached maturity at the end of 75 days.

Barley, Hordeum vulgare.

The root development of barley growing in an adjoining plat was determined, as was also that of wheat, at the same intervals as for oats. At the first examination, on May 1, the evenly developed crop had a height of 2.5 to 3 inches. Nearly all of the plants had a second leaf 1 to 2 inches long. The general root habit as regards fineness of roots, branching, and lateral spread is almost identical with that of wheat and oats, being somewhat intermediate between the two. The maximum depth of root penetration was 10 inches and unbranched laterals 0.3 to 1 inch in length were fairly abundant, except near the root ends.

On May 15 the plants averaged 4.5 inches in height, some had 2 or 3 tillers with the second leaf unfolding, and practically all had developed 3 or 4 leaves. Plants of average size had from 5 to 11 roots. The longest reached a depth of 2.2 feet, but most of them ended at about the 1.2-foot level. The general working depth of the root system was 9 inches and the maximum lateral spread 8 inches. The older portions of the root system were well furnished with primary laterals varying in length from 1 to 1.5 inches, some of which had secondary branchlets 0.3 inch or less in length. Young, entirely unbranched roots ran off horizontally or obliquely to distances of 1 to 3 inches. Where roots entered crevices in the soil, they were densely covered with short branches and root-hairs. Below 11 inches only a few short branches occurred. As in the other cereals studied, the glistening-white, deeper roots often ran several inches without branching.

An examination of the development of barley on June 3 showed that the plants had made a marked growth of both tops and roots. They averaged 8 inches tall, although some were 11 inches. 5 or 6 leaves had developed on each plant, and many had 1 to 3 tillers, the oldest being from one-third to one-half as tall as the parent. The area to be occupied by the mature root system was at this time fairly well delimited, except in depth. Of the 10 to 17 main roots on a plant, some descended only slightly outward and then downward to a depth of 1.7 to 2.7 feet, the deepest reaching 3.2 feet. Many others extended rather horizontally or obliquely for horizontal distances of 5 to 8 inches from the plant, the shallowest ending in the surface 3 inches of soil. Thus, barley roots are somewhat nearer the surface at this stage than wheat or oats. The most superficial, younger roots, and indeed nearly all of those in the surface 1 or 1.5 feet of soil, were clothed with an abundance of laterals, often as many as 15 per inch, and an inch or less (rarely more than 2 inches) long. Below 1.5 feet laterals were far less abundant, rather irregularly distributed (3 to 8 per inch), and also much shorter. Secondary laterals were in no case abundant, although some from a few millimeters to an inch in length were found. The last 6 to 12 inches of the rapidly growing roots, and especially the deeper ones, were entirely devoid of branches.

The soil area thus inclosed by the developing root system was only fairly well occupied at this time to a working level of about 1.8 feet.

Barley plants at Peru, 54 days after planting, gave a greater height growth, while maximum root penetration exceeding that of these 63-day-old plants by 1.3 feet. Moreover the differentiation of the root system into two parts was rather clearly marked (p. 18).

Plants 80 days old were examined on June 19 and 21. They averaged 2.3 feet in height, with a maximum development of 2.7 feet. Many plants had no tillers, others had 1 to 7, with an average of about 2 or 3. The crop was just beginning to blossom. A great tangle of well-branched roots spread laterally from medium-sized plants to distances of 7 to 10 inches and occupied the soil thoroughly to the working level at 2.7 feet. Even below this level roots were quite abundant for 8 or 10 inches, the longest extending to a total depth of 4.4 feet. Roots were more abundant in the surface 3 inches of soil than were those of either wheat or oats. The development of secondary rootlets was very similar to that of oats and wheat. Wheat, however, was found to be more abundantly supplied with finer rootlets than either oats or barley.

In the lowland plats, at this time, the crop was about 2.7 feet in average height and had been in blossom for 2 or 3 days. The working depth of the roots was 3 feet, while the longest reached the 4.5-foot level. The greater abundance of surface roots as compared with wheat and oats was clearly evident.

A final examination of the root system, shortly after the grain was harvested on July 12, showed, as in the case of the other cereals, that the working level was somewhat deeper (2.9 feet), as was also the maximum depth (4.7 feet). The area of soil under the plants was even more completely filled with great masses of finely branched roots, the whole forming an exceedingly efficient absorbing system. On the lowland area the roots of mature barley plants had a working depth of 3.3 feet, while several of the longer roots were traced to depths of 5.4 feet.

Wheat, Triticum æstivum.

The root development of Marquis Spring wheat, growing in an adjoining plat, was determined at the same intervals as the oats. On May 1 the wheat had an average height of 2.5 inches, although many plants were an inch taller. The stand was good and the crop quite evenly developed. The second leaf was from 1 to 3 inches long in nearly all plants, while some were unfolding the third leaf. The root system, while very similar to that of oats, was somewhat more extensive. The number of roots on the large lot of plants examined varied from 3 to 8, with an average of about 6. The maximum depth of penetration was 15 inches, although most of them were much shorter, so that the working depth was only about 6.5 inches. The greatest lateral spread was 5 inches. The root diameter, which was almost identical with that of oats and barley, was seldom over 0.5 mm. Laterals occurred at the rate of about 5 to 13 per inch. These varied in length from only 2 mm. to 1.3 inches. They were entirely unbranched. On the youngest portions of the roots practically no laterals occurred, but as a whole they were somewhat more numerous than on the oats or barley (fig. 22). Environ-

mental conditions during the several intervals of growth have already been given in the discussion of oat. It is of interest to note that wheat planted May 15 was further developed after a growth period of 15 days than were the 31-day-old plants just described. The former were 3 or 4 inches tall, had unfolded 3 leaves, and the roots were developed proportionally. But even these had not made the rapid root growth recorded by Rotmistrov (1909 : 33).

Plants 45 days old were examined on May 15. The crop had an average height of 4 inches, the tallest plants exceeding this by only 0.5 inch. Some plants had 2 or 3 tillers, the largest of these offshoots having 2 or 3 leaves. The root development again execeded that of oats, with a maximum depth of 2.3 feet, a general working level of about 10 inches, and an extreme lateral spread of 8 or 9 inches (fig. 23 A). 8 to 10 roots per plant were commonly found; many new roots only 1 or 2 inches in length occurred on the plants that were tillering. In the surface 6 or 8 inches of soil, lateral roots 1 to 3 inches in length and many more shorter ones were found. These had a few very fine secondary laterals only a few millimeters long. Below 10 inches the main roots became glistening white, larger in diameter, and the laterals very sparse. As a whole, wheat roots are somewhat finer and more thread-like than those of oats or barley. Wheat planted May 5, when 25 days old, showed more advanced growth than these. It had reached a height of 4 or 5 inches, was developing the fifth leaf, and had tillers with 2 or 3 leaves. A third examination of wheat was made on May 29 and 31, when the plants, now 60 days old, had reached an average height of about 8 inches and had grown 4 to 6 leaves. A few plants were 12 inches tall. Nearly all had 2 or 3 and some 4 to 7 tillers; the largest of these had 3 or 4 leaves. The roots, during the 15-day interval since the last examination, had increased to a total of 11 to 18 per plant. Many penetrated deeper than before, others spread obliquely downward, and, with the increase of laterals both in number and length, began to fill in the soil area already delimited at the earlier stage. The average maximum root penetration was 2.6 feet, but a few roots ended 5 inches deeper. The last 8 to 12 inches of root in the very moist subsoil were glistening-white, ran vertically downward, and were not only free from branches, but, like the deep oat roots, were not well clothed with root-hairs. The working depth was about 1.5 feet. The maximum lateral spread was about 10 inches, although few roots spread so widely (fig. 23 B).

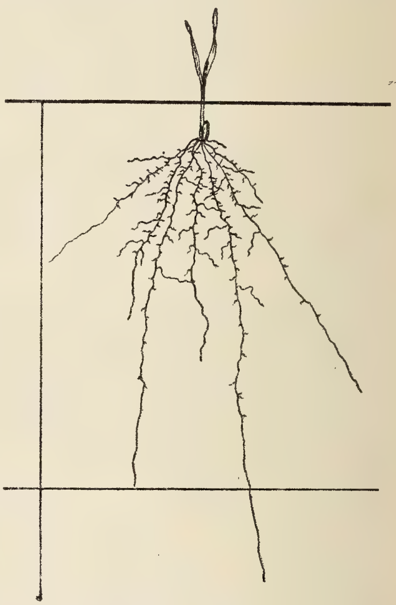


Fig. 22.—Wheat 31 days old.

Further studies were made on June 19 and 21, when the crop was in blossom. The plants averaged about 2.2 feet in height, the tallest reaching 2.8 feet. The number of tillers per plant varied from single-stemmed plants to those with 7 or 8 tillers, but the average was about 2. 20 days of growth had

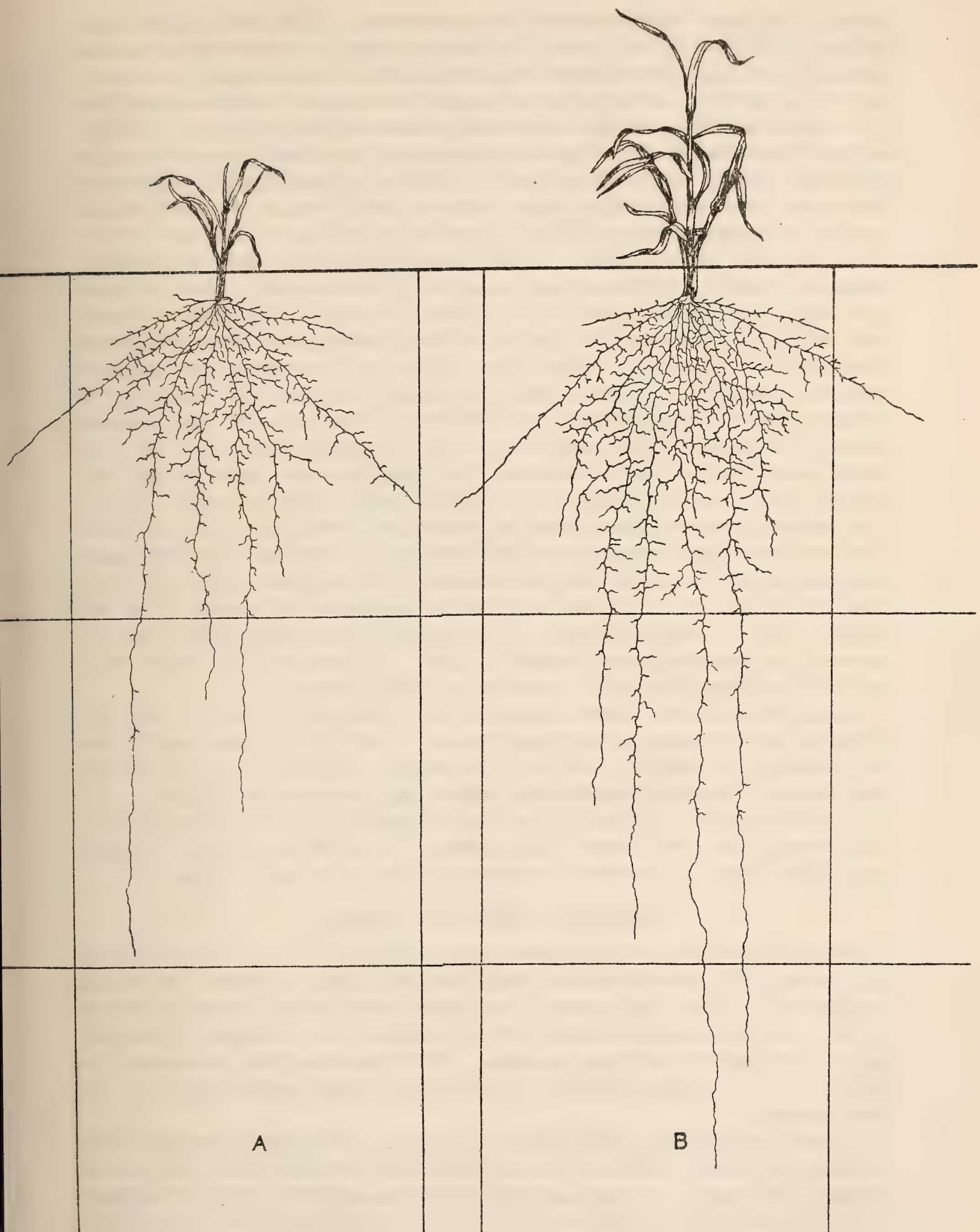


FIG. 23.—A. Wheat 45 days old. B. Wheat 60 days old.

shown a profound development of the root system. The working level had reached a depth of 2.8 to 3.1 feet; the longest roots penetrated the soil rather vertically downward for 4.8 feet; the lateral spread had increased to a maximum of about 1 foot, while a vast network of rebranched laterals occupied an area of soil extending roughly 0.8 foot on all sides of the plant and to a depth of 2 or 3 feet (fig. 21 B). The total number of roots had now increased to 20 or 25, varying with the number of tillers on a parent plant. Many of these were more superficially placed than in earlier stages of development, running off rather horizontally or obliquely and ending in the first 3 to 8 inches of soil. In the surface 2 feet especially, laterals were exceedingly abundant, usually 5 to 9 occurring on an inch of root-length. Many of these were short and few exceeded 3.5 or 4 inches in length. Secondary laterals were not at all abundant. In the second foot the branches were mostly less than an inch in length. Below 2 feet branching was somewhat less pronounced, especially as regards length of primary rootlets and abundance of secondary ones. In the fourth and fifth foot numerous roots were characterized by unbranched laterals about 0.3 inch in length, but only 1 to 4 occurred on an inch of root. On others the branches were much thicker but shorter, and frequently occurred to within an inch of the root-ends. Again, other root-ends were without branches for several inches back from their tips.

In the lower plats the wheat at this time was 2.6 feet tall and blossoming had just begun. As with the other cereals, tillering was much more pronounced (average of 3.2 stems per plant as compared with only 1.7 in the upland) and the stand was thick. The maximum root penetration was 4.8 feet and the working depth about 3.1 feet. No marked differences were noted in the branching habit or extent of lateral spread.

A final examination a few days after harvesting the grain on July 15 showed no great change in root development. As with oats and barley, the roots, except the deepest ones, were somewhat shriveled and more brittle than before. The depth and lateral spread had increased only slightly. In the lower crop plats the working level had deepened to 3.5 feet, but no roots were found below the former 4.8-foot level. As a whole, the root system was a little finer and somewhat more extensive than that of oats.

ALFALFA, MEDICAGO SATIVA.

This crop was sowed on the upland plats on March 31, in an area adjoining the cereals. The environmental conditions until May 1, when the initial examination of root development was made, have already been described (p. 42). At this time the plants were not over 0.5 inch in height. The first pair of true leaves was just unfolding. The tap-roots had penetrated to depths of 5 or 6 inches and the first laterals were just beginning to form on some plants.

A second examination was made on June 2. The plants averaged only 2.5 inches in height, although certain individuals exceeded this by 0.5 to 1.5 inches. The stage of development of both tops and roots is shown in figure 24 A. Several roots reached depths of 1.5 feet, while two of the plants examined had roots 1.8 feet long. Practically no branches occurred in the surface 1 or 1.5 inches of soil, but below this level as many as 10 or 12 per linear inch of tap arose. These varied from a few millimeters to 3 inches in length;

the longer ones had a few secondary laterals, mostly less than 0.4 inch long. On smaller plants nearly all of the laterals were less than 0.5 inch in length and extended out in a more or less horizontal direction or turned somewhat obliquely downward. On all roots the 2 to 4 inches nearest the tip were glistening white and unbranched. Nodules were abundant.

A third examination of the root development was made July 24 on both upland and lowland areas. The plants were 115 and 106 days old respec-

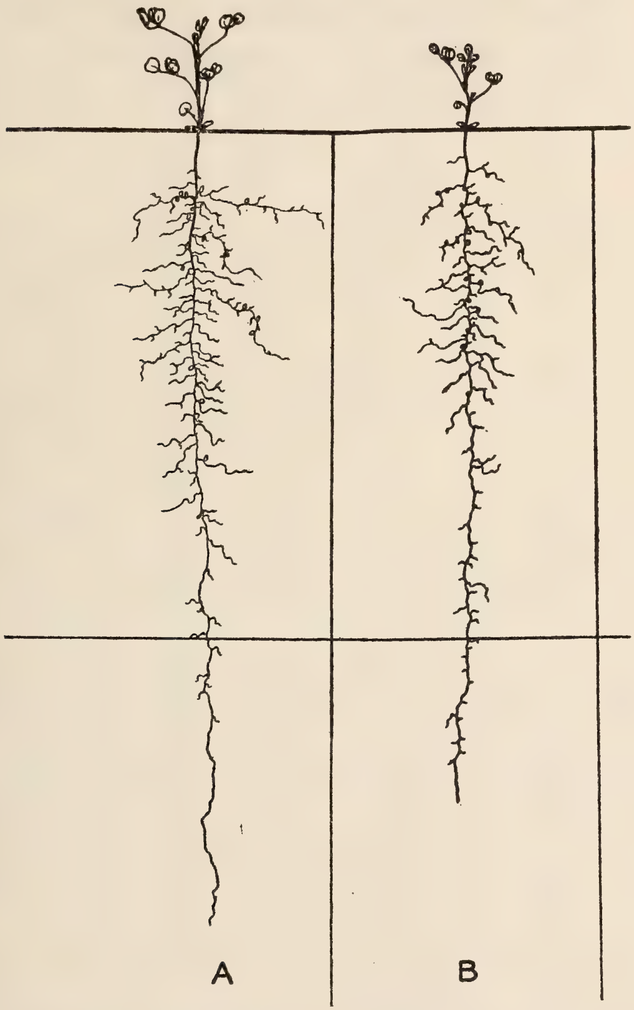


FIG. 24.—A. Alfalfa 63 days old. B. Sweet clover 63 days old.

tively. Those in the upland area averaged 1.1 feet in height, the tallest reaching 1.4 feet. They had developed normally in every way, but were somewhat affected by "white spot." On the lowland the crop averaged 1.7 feet high, the tallest plants reaching 2 feet. It has already been pointed out (p. 45) that June was a very favorable month for growth. Excellent growth con-

ditions also prevailed throughout July. Well-distributed rains furnished abundant soil-moisture (table 10); soil and air temperatures and humidity were favorable (fig. 20), and evaporation was not excessive (table 11).

The roots on the upland had penetrated to a maximum depth of 5.2 feet and were fairly abundant to the 4.2-foot level. Those on the lowland were slightly deeper. The greatest depth of penetration was 5.7 feet and several occurred at the 5-foot level. In both areas the tap-root was the prominent

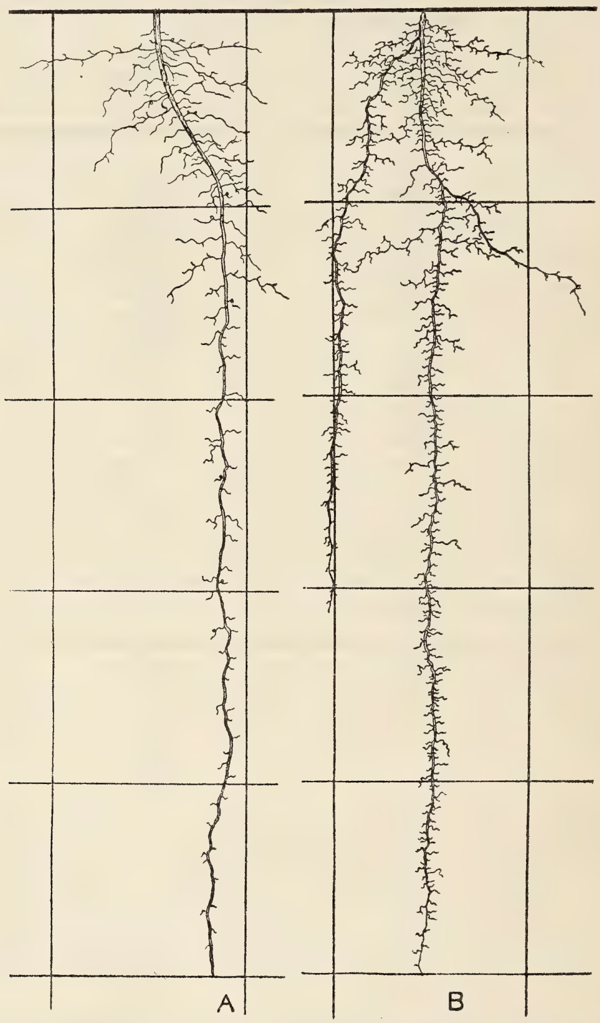


Fig. 25.—A. Alfalfa 132 days old. B. Sweet clover 115 days old.

feature, varying from 3 to 5 mm. in diameter. Laterals were not abundant below the surface 1.5 foot of soil. The longest did not exceed 6 or 8 inches. The roots penetrated nearly vertically downward and were furnished at irregular intervals with short, mostly poorly branched or unbranched rootlets. These occurred at intervals of an inch or less, becoming smaller near the

tip. Nodules occurred to depths of over 3.5 feet. Little difference was noted in the number or length of branches of roots excavated in the lowland.

A final examination in the upland plats was made on August 10. At this time the tallest plants were 1.5 feet high, while the crop averaged 1.3 feet. Growth conditions had continued favorable, soil-moisture was abundant, especially in the deeper layers, and root growth continued. Many of the roots had reached a depth of 5 feet, while some penetrated 2 to 6 inches deeper. The tap continued to assume the dominant rôle, and no change occurred in branching habit. The older laterals were longer and extended laterally often more or less parallel with the soil-surface for distances of 6 to 10 inches or turned obliquely downward, usually making wide angles with the tap (fig. 25 A). Root development in both upland and lowland areas during 1919 was very similar to that just described (Weaver, 1920 : 127).

Sweet Clover, Melilotus alba.

This crop was planted on the same day as alfalfa (March 31) in level plats adjoining those of the cereals. On May 1, when the plants had reached a maximum height of 0.5 inch, the root systems were examined. None of the roots reached depths greater than 3 or 4 inches.

A second examination was made on June 2, when the crop was 1.5 to 2 inches tall. Many roots extended to depths of 0.9 to 1.2 feet and a few reached the 1.4-foot level. Secondary laterals were fairly abundant, as were also the bacterial nodules. The branching habit was very similar to that of alfalfa of the same age (*cf.* figs. 24 A and 24 B).

On July 24, when the crop had reached an average height of about 1.3 feet, root development was again examined. Roots were abundant to the 5-foot level, while some penetrated the moist soil to a distance of 5.5 feet. On the lowland, where the tops were better developed (average height about 2.2 feet) the root development was almost identical as regards depth of penetration, abundance of branching and lateral spread, and presence of nodules at all depths. The strong tap-roots varied from 4 to 6 mm. in diameter, penetrated almost vertically downward, and tapered rapidly. Major branches were few, usually only 1 to 3 per plant. These originated at various depths, sometimes near the surface and again as deep as 2 or 3 feet. Like the main root, these larger branches, sometimes 2 or 3 feet long, were furnished with rather numerous relatively short and mostly poorly branched sublaterals. The most marked development of laterals on the tap occurred in the surface foot of soil. No branches extended to horizontal distances greater than 8 or 10 inches from the tap and most of them were very much shorter (fig. 25 B).

Comparison of Root Systems.

Just as the native species examined in the prairies at Peru were found to be more deeply rooted than those at Lincoln (Weaver, 1919 : 15), so too the crop plants show clearly this difference in root habit. Table 12 summarizes the development of the crops at Lincoln. When this is compared with a similar summary for the Peru crops (table 1), striking differences are at once apparent. Oats at Peru reached a maximum depth of 6.7 feet, at Lincoln only 4.2 feet. The maximum lateral spread was 1.4 feet at the former station and only 0.8 foot at the latter. Differences in the root development of

Marquis wheat and barley were scarcely less striking, the greater development of the root system at Peru being consistent for all crops examined. Nor is this difference correlated with height-growth, for the average height-growth of the several crops at Lincoln during 1919 and 1920, especially when the lowland plats are included, was not unlike that at Peru. Moreover, the differentiation of root systems into a more or less distinctly shallow portion and a more deeply penetrating one was much more marked at the latter station. The root habit of the cereals at Lincoln was consistent during the

TABLE 12.—*Development of upland crops at Lincoln, Nebraska, 1920.*

Crop.	Age of plants.	Average height.	Stage of development.	Working depth.	Maximum depth.	Maximum lateral spread.	Remarks.
	days.	*feet.*		*feet.*	*feet.*	*feet.*	
Oats, White Kherson	31	0.2	1 or 2 leaves.	0.4	0.7	0.3	5 to 7 roots.
	45	0.3	4 leaves.....	0.7	2.0	0.5	7 to 14 roots; no tillers.
	60	0.7	7 to 9 leaves.	1.5	2.7	0.7	16 to 27 roots; 0 to 2 tillers.
	80	2.0	In blossom..	2.3	4.1	0.8	0 to 5 tillers per plant.
	103	2.0	Mature.....	2.7	4.2	0.8	
Wheat, Marquis	31	0.2	2 or 3 leaves.	0.5	1.3	0.4	3 to 8 roots.
	45	0.3	4 leaves.....	0.8	2.3	0.7	8 to 10 roots; 0 to 3 tillers.
	60	0.7	5 or 6 leaves.	1.5	3.0	0.8	11 to 18 roots; 2 to 7 tillers.
	80	2.2	In blossom..	3.0	4.8	1.0	20 to 25 roots; 0 to 8 tillers.
	106	2.2	Mature.....	3.2	5.0	1.0	
Barley, Manchuria	31	0.2	2 leaves.....	0.5	0.8	0.4	3 to 7 roots.
	45	0.4	3 or 4 leaves.	0.7	2.2	0.7	9 roots; a few tillers.
	63	0.7	5 or 6 leaves.	1.8	3.2	0.7	10 to 17 roots; 0 to 3 tillers.
	80	2.3	In blossom..	2.7	4.4	1.0	0 to 7 tillers.
	103	2.3	Mature.....	2.9	4.7	1.0	

years 1919 and 1920, both of which, except for a late, cold spring in 1920, had growing-seasons very favorable for crop development. Just how much the modification of the root habit at Peru was due to the drought which prevailed during 1919, and how much it was affected by other factors, such as soil texture, fertility, etc., will be further discussed when the 1921 root growth at the several stations is compared in chapter 5. A summary of earlier investigations on the root development of crop plants in the true prairie may be found in chapters 6 and 7 of "Root development in the grassland formation."

III. INVESTIGATIONS AT PHILLIPSBURG, KANSAS, IN 1920.

A third station was maintained during 1920 at Phillipsburg, in north-central Kansas. This station which is about midway between Lincoln, Nebraska, and Burlington, Colorado, has an altitude of 1,935 feet and an annual precipitation of 23 inches. The crop plats occupied an area, quite typical of the rolling topography, on a hillside which sloped gently to the south and east.

The fertile soil is a mellow dark-brown silt-loam of the Colby series. At a depth of 1 to 1.2 feet it is slightly lighter in color and contains enough clay to be quite sticky, although when wet it is dark in color to a depth of 2 feet. Below this level it is light yellow, and shows throughout its loess origin. The first 4 feet have a water-holding capacity of about 66 per cent. Excavations for root examinations near this station on June 27, 1919, showed that the soil was thoroughly moist to a depth of at least 8 feet and repeated excavations in the plats during 1920 failed to reach the limit of water penetration.

The crops grown here were from the same lot of seed as that used at Lincoln and Burlington. Moreover, the methods and rate of seeding, etc., were the same as those employed at the other stations. The field had been broken for several years; the preceding crop was wheat. It was plowed to a depth of about 5 inches, harrowed, and brought to good tilth before the crops were hoed in on May 7. The late date of planting, unavoidable because of weather conditions, should be noted, since it bears a close relation to the later maturing of the crops and the injury done by a rust epidemic.

Oats, Avena sativa.

The first examination of root development was made on June 10. The crop was in a thriving condition, and, although only 34 days old, had reached an average height of 9 inches. The parent plants had 5 or 6 leaves each and had tillered rather freely. Many had 2 or 3 tillers each. Some of the offshoots were of equal or nearly equal height with the parent plants, while others were only 1 or 2 inches high. The stand was quite uniform and the plants of even height.

The period as a whole had been one favorable to rapid growth, and, in fact, the crop was as far developed as the oats at Lincoln at the age of 55 days (i. e., on May 25). At the time of seeding 16 per cent available water was present in the oat plats in the first 2 feet of soil and 11 or 12 per cent to a depth of 4 feet. Frequent, well-distributed showers during the remainder of May, totaling 3.4 inches, kept the soil in good condition. On June 2, 12 per cent available water was present to 4 feet depth, except that the surface 6 inches had only 10 per cent. Similar water-content conditions prevailed until June 10 (table 13).

The temperature of the soil from June 2 to 10 varied from 59° to 73° F. at a depth of 6 inches, with an average daily temperature of 65° F. The air-temperature during the same interval varied from 51° to 90° F. with a mean of 69° F. The mean air-temperature for May was 60.6° F. The evaporating power of the air (June 2–10) was only 11 c. c. daily.

An examination of the roots showed that they had made a good growth and were remarkably similar in development and distribution to those of the crops

grown at Lincoln. In fact, the similarity was so great in case of the cereals that detailed descriptions need not be given. The lateral spread was about 5 to 7 inches. The working depth was 2.1 feet. One root was traced to a maximum depth of 3.8 feet and several were found at the 3.5-foot level. Below 2.6 feet the thick, white roots were entirely devoid of branches. Thus the root system was more deeply seated than that of oats at Lincoln on May 30.

TABLE 13.—*Water-content in excess of hygroscopic coefficient in crop plats at Phillipsburg, Kansas, 1920.*

Date.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
May 7	16.8	16.7	15.8	12.6	11.0
June 2	9.7	12.2	12.7	12.8	12.4
June 10	9.1	13.0	11.2	....	....
June 24	8.5	7.6	9.0	10.3	....
July 1	−0.4	0.9	2.9	....	....
July 9	−3.1	2.5	0.9	1.3	3.9
July 21	−3.3	−1.2	−0.4	0.4	0.9
Aug. 4	2.3	4.0	2.5	2.2	2.1
Aug. 26	0.1	1.5	−2.1	−0.9	0.9
Wilting coefficient	13.3	13.3	13.4	13.5	13.1
Hygroscopic coefficient	10.6	10.6	10.9	10.6	10.7

On July 9 the oats was well past the dough stage of grain development. The crop averaged 2.6 feet in height. Counts on selected square-meter areas showed that the plants had an average of 2.3 tillers each. The crop was slightly damaged by grasshoppers and also somewhat affected by stem rust, *Puccinia graminis avenæ*. Indeed, by the time of harvest (July 20) the rust epidemic was so severe that the grain was very light and of very poor quality.

TABLE 14.—*Average daily evaporation at Phillipsburg, Kansas, 1920.*

	c. c.		*c. c.*
June 2 to 10	11.0	July 15 to 21	25.9
June 10 to 17	26.9	July 21 to 28	29.5
June 17 to 24	12.3	July 28 to Aug. 4	21.1
June 24 to July 1	24.5	Aug. 4 to 11	13.8
July 1 to 8	32.2	Aug. 11 to 18	13.0
July 8 to 15	30.6	Aug. 18 to 26	24.2

The root system by this time had penetrated the loess soil to a working depth of 3.3 feet. A maximum depth of 6 feet was recorded for a few of the longest roots, while at 5.5 feet depth they were not at all uncommon. Thus, the root depth exceeded that at Lincoln (4.2 feet) and nearly equaled that at Peru (6.7 feet). The root extent was greater than that of Texas Red oats (4.8 feet) excavated a few miles distant, but in similar soil, in June 1919 (Weaver, 1920 : 119).

The clue to this marked root development is apparently to be found in an examination of the texture and water-content of the soil and the aerial conditions causing water-loss. In general, the mellow soil during this interval was relatively dry when compared with conditions at Lincoln, while the evaporating power of the air was greater than at the latter station. This seems to have stimulated root-growth in the deeper soils where available

water was present. Only 1.96 inches of rain fell during this period (June 10 to July 9), and about 20 per cent of this occurred in 9 light showers which had little or no appreciable effect upon water-content. An examination of table 13 reveals the scarcity of available moisture, which was entirely exhausted from the surface 6 inches of soil on July 1 and 9. Throughout the period the evaporating power of the air was relatively high, about 24 c. c. daily (table 14). The average daily air-temperature ranged from 64° to 76° F., maximum temperatures of 88° to 99° F. not being unusual. The soil-temperature at 6 inches depth varied from 65° to 77° F. (fig. 26).

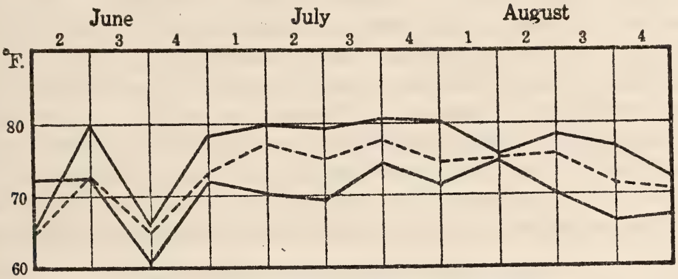


Fig. 26.—Average day and average night air-temperatures and average daily soil-temperature (broken line) at Phillipsburg, 1920.

Barley, Hordeum vulgare.

On June 10, when the barley roots were first examined, the crop was in good condition and had an average height of about 10 inches. The parent plants had from 4 to 6 leaves each. They frequently had 3 to 5 tillers, and some of these were almost as tall as the original shoot. The stand was fairly even and the plants of uniform height. The roots had a working depth of 2.5 feet, a lateral spread of about 0.5 foot on all sides of the plant, and reached a maximum depth of 4.3 feet.

A second examination was made on July 9, when the crop was 2.4 feet high and in the dough stage of development. It was badly affected by stem rust, *Puccinia graminis tritici*, and the grain, when ripe, was light and wrinkled. The root system had a working depth of about 3.3 feet; several roots were traced to a depth of 6 feet and a few even to 6.7 feet. Root habit as regards lateral spread, degree of branching, etc., was nearly identical with barley grown at Lincoln.

Wheat, Triticum æstivum.

At the time of the first examination (June 10), the Marquis Spring wheat was about 7 inches in average height and of good, even stand. It had tillered more freely than either of the other cereals, 6 offshoots not being uncommon. Some of the tillers were as tall as the parent plants, and, like them, had 4 or 5 leaves each. The crop was not only shorter above ground than the other cereals, but the root system was much more poorly developed. The working depth was only 2.1 feet (compared with 2.5 feet for barley), while practically no roots penetrated beyond the 3.7-foot level.

On July 9, when again examined, the crop was 2.3 feet in average height. The wheat was badly rusted, and the grain, now beyond the dough stage, was shriveled and light when harvested on July 20. The surface-rooting habit was similar to that at Lincoln, the roots having a maximum lateral spread of a foot. The working level now reached 3 feet, while maximum root penetra-

tion was about 5.8 feet. The long, glistening-white, unbranched root-ends in the deeper soil were very characteristic. The soil was quite moist to all depths examined, about 8 feet.

Alfalfa, Medicago sativa.

The root development of this crop was studied at the same time as that of the cereals. On June 9 the plants were from 4 to 5 inches in height and growing vigorously. The stand was fairly uniform. Numerous tap-roots were found terminating at depths of 2 to 2.7 feet and the soil was well filled with roots to the 1.3-foot level. Tubercles were abundant. The branching habit, number of laterals, etc., were so nearly identical with that described at Lincoln that further description is unnecessary (*cf.* fig. 24 A).

By July 10 the larger alfalfa plants were 14 inches tall and in good condition; a few were beginning to blossom. Although the surface 1.5 feet of soil was quite dry, the deeper soil was moist to the maximum depth of root penetration, about 5 feet, and, in fact, for several feet beyond. As at Lincoln, the absence of large lateral branches was a characteristic feature of the root habit, which agreed in all essentials with plants of similar age described at the former station.

Sweet Clover, Melilotus alba.

When sweet clover was first examined (June 10), the tallest plants were only 3 inches high and the average height of the crop was only 2 inches. However, the underground parts were well advanced in development. The surface 1.7 feet of soil was well filled with roots and an average maximum depth for many plants was 2.5 feet. Two especially deep ones penetrated to the 3-foot level. All of the numerous laterals, which were similar to those at Lincoln in number and extent, were well supplied with nodules.

On July 9, when the crop had reached a height of 1.3 to 1.7 feet, a second examination was made. The above-ground parts were greatly exceeded in extent by roots. Some of the larger tap-roots were 6 or 7 mm. in diameter and reached depths of 4.5 to 5.7 feet. The long, vertically descending, and unbranched root-ends were developing rapidly in the moist subsoil (*cf.* fig. 25 B).

Summary of Crop Development.

The crops at Phillipsburg were planted later than at the other stations and before harvest were badly injured by a rust epidemic which materially reduced the yield. Early spring conditions were favorable to growth and the stand in every case was quite uniform, the cereals tillered well, and the crops developed rather uniformly and more rapidly than those planted earlier at the other stations. Oats, wheat, and barley, when matured, averaged 2.6, 2.3, and 2.4 feet in height respectively, while the height of alfalfa and sweet clover was 1.2 to 1.7 feet. Responding, apparently, to the environment during June and July, which coupled high water-loss with a relatively dry surface-soil, the crops developed root systems which extended far into the deeper moist soils. Thus, the roots of wheat and oats penetrated to about 6 feet and those of barley even deeper. Alfalfa and sweet clover, when only 64 days old, reached depths exceeding 5 feet. The abundance of laterals, degree of branching, and general root habit corresponded otherwise with crops grown in less arid regions. These results are not at variance with those obtained at the same and neighboring stations during 1919, and also check well with the root habits of the native mixed-prairie vegetation.

IV. INVESTIGATIONS AT BURLINGTON, COLORADO, IN 1920.

Crops were also grown during 1920 at Burlington, a station in the short-grass plains of eastern Colorado, having an altitude of 4,160 feet and an average annual precipitation of 17 inches. The crops which were from the same lot of seed as that used at Lincoln, were planted at the same rate per acre and in the same sized plats as those described. In fact, except for the normally later sowing (April 15) due to a later spring at the higher altitude, the experimental plats were duplicates of those at the former station. The soil is a rich, brown, fine sandy loam, very compact and hard when dry. It has a water-holding capacity of 65 to 70 per cent to a depth of 4 feet. At a depth of 2 to 2.5 feet it is underlaid with a so-called hardpan. Soil analyses show that the concentration of colloidal clay and carbonates in the subsoil is sufficient to give rise to a hardpan, i. e., a much more compact stratum of soil relative to that above or below it, upon its becoming completely dried out (Weaver and Crist, 1922). An examination of table 15 shows that silt constitutes about one-third of the soil at all depths, while the sand decreases and the clay increases in amount to 4 feet.

TABLE 15.—*Mechanical analyses of soils from Burlington, Colorado.*

	Depth of sample, in feet.				
	0.0 to 0.5	0.5 to 1.0	1 to 2	2 to 3	3 to 4
	p. ct.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
Coarse gravel	0.0	0.0	0.0	0.0	0.0
Fine gravel	0.0	0.0	0.0	0.0	0.0
Coarse sand	0.0	0.0	0.0	0.0	0.0
Medium sand	0.13	0.14	0.17	0.13	0.10
Fine sand	2.6	2.2	1.9	1.5	0.9
Very fine sand	48.6	49.1	46.7	45.5	42.2
Silt	33.4	32.5	32.0	31.0	34.2
Clay	15.3	16.1	19.3	21.9	22.6
Hygroscopic coefficient	10.9	10.9	12.2	12.0	11.4

Chemical analyses show that carbonates are practically absent in the surface soil, but increase rapidly with depth, and in the hardpan layer, which appears somewhat chalky in color, they often reach concentrations of 5 or 6 per cent. Table 16 shows that the soils are not acid, the carbon dioxide increasing very rapidly with depth and being very high at 2 to 4 feet. These soils are rich in phosphorus and potassium and have a sufficient supply of nitrogen. Thus, all the critical elements are present in abundance.

Hardpan is found rather generally throughout the short-grass plains association. The native short-grasses compact the soil so firmly that run-off is usually high, while the water penetrates very slowly. This is indicated by the frequent occurrence of dry stream-beds of various sizes. Shantz (1911) has shown that the average run-off from the short-grass sod at five stations in this region was 37 per cent of the total rainfall (maximum 55 per cent), while that from variously tilled crop areas was almost as great. After

heavy rains three days were required for the water to penetrate to a depth greater than 6 inches. This high run-off has been repeatedly confirmed by the writers while the penetration of water, when applied to moisten the surface soil prior to root examinations, was exceedingly slow. The excellent root development of native plants in the surface 1.5 to 2.5 feet of soil fits them to absorb the water readily, and they help to prevent deep water penetration (Weaver, 1919, 1920). This is of especial significance in this study, since cultivated plants modify their root distribution in a manner similar to that of the native vegetation.

Table 16.—*Chemical analyses of soils from Burlington.*[1]

	Depth of sample in feet.				
	0.0 to 0.5	0.5 to 1.0	1 to 2	2 to 3	3 to 4
	p. ct.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
Acidity	none	none	none	none	none
Carbon dioxide	0.03	0.30	1.71	2.10	2.60
Volatile matter	4.67	3.13	3.11	3.34	2.84
Phosphorus pentoxide	0.189	0.504	0.428	0.406	0.525
Sulphur trioxide	0.007	0.017	0.006	0.006	0.005
Potassium oxide	2.32	2.39	2.45	2.51	2.22
Nitrogen	0.184	0.130	0.101	0.086	0.084

[1] Methods used were the same as described on p. 32.

The field in which the crop plats were located was a portion of a vast level tract surrounded on three sides by fields of wheat, corn, and Sudan grass, respectively. The sod had been broken in the spring of 1918 and planted to Sudan grass. After this was harvested the ground was plowed late in the fall, and the next spring it was repeatedly harrowed and a good seed-bed formed before the experimental crops were hoed in.

Wheat, Triticum æstivum.

On June 12, 58 days after planting, the Marquis Spring wheat was thoroughly examined. The plants averaged 10 inches in height, the tallest reaching 12 inches. They were well-tillered, many having from 4 to 8 shoots. The parent plants had an average of about 6 leaves each. Many of the tillers were 6 to 10 inches high, but others were only 1 or 2 inches. The wheat was somewhat fired at the base and many of the younger tillers were dead and dry, as were also the two or three basal leaves on the larger tillers and parent plants. However, a part of this injury was the effect of frost. The stand, like that of the other cereals, was thin but fairly even, germination having occurred under rather favorable moisture conditions. On April 15, at the time of planting, more than 10 per cent of available moisture was found in the surface foot of soil (table 17). Although soil samples were not taken again until June 3, it seems clear from the rainfall records that moisture conditions were quite favorable, at least until the latter part of May. During the last half of April a total of 1.4 inches of rain fell at four well-distributed intervals, while from May 1 to 15, four other favorably distrib-

uted rainy periods gave a total of 1.2 inches. In fact this, coupled with the high fertility of the soil (table 16), undoubtedly accounts for the very marked early growth and the abundance of tillers, both phenomena being detrimental to the crops at a later period.

TABLE 17.—*Water-content in excess of hygroscopic coefficient in crop plats at Burlington, 1920.*

Date.	0 to 0.5 foot.	0.5 to 1 foot.	1 to 2 feet.	2 to 3 feet.	3 to 4 feet.
April 15	22.0	10.5	0.5	−0.1	−0.4
June 3	5.3	6.4	3.1	5.1	−0.6
June 12	0.4	3.8	1.2	...	...
June 25	6.4	1.7	0.8	2.7	1.6
July 2	−2.0	−1.1	0.0	...	...
July 8	−2.0	−0.4	−1.4	0.7	1.8
July 20	0.5	−2.6	−2.8	−0.5	2.0
August 5	4.4	0.0	1.3	0.0	−1.9
August 24	−0.7	−0.9	−2.2	−2.5	−1.8
Wilting coefficient	13.3	13.3	14.0	14.5	14.0
Hygroscopic coefficient	10.9	10.9	12.2	12.0	11.4

On June 3 a small margin of available water (3 to 5 per cent) still occurred in the first 3 feet of soil, but by June 12 a deficiency was indicated by the behavior of the plants. As a result of the drought (no rain in sufficient amount to wet the soil had fallen from June 1 to 12), many of the leaves were rolled and some did not recover their turgidity even during the night.

Temperatures during the last half of April were low, falling below 32° F. on 11 nights. The mean monthly temperatures for April and May were 41.2° and 57.8° F. respectively. Frost occurred on May 15 and did some injury to the crops. Only 3 clear days occurred in April and 5 in May. During the last week of this interval the soil-temperature at a depth of 6 inches (in an adjacent area of grassland) averaged 65° F. while the air temperature gave an average of 80° F. during the day (maximum 100° F.) and 57° F. by night (minimum 43° F.). The evaporating power of the air was 47 c. c. per day, 85 per cent of which normally occurs during the hours of daylight, the humidity often falling to 15 per cent or less. These aerial conditions, coupled with the low water-content of the soil, readily explain the semi-wilted condition of the crops. The soil in the plat where the wheat was excavated was underlaid at a depth of 2.7 feet with a rather poorly developed, light-colored hardpan, which, like the more ashy loess beneath, was very dry.

Root counts were made on a large number of plants. The number of roots varied from 15 to 19. Not infrequently 5 to 9 of the younger ones had grown an inch or two and died, apparently from drought. The extreme depth reached by several roots was 2.5 to 2.7 feet, although a single root was traced in the soil of an ancient rodent's burrow, where water had penetrated, to a depth of 3.3 feet. However, the working depth of the root system as a whole was only 1.3 feet. The plants had a wide lateral spread, and not infrequently roots extended laterally for 10 or 12 inches in the surface 6 inches of soil. Others gave a maximum horizontal spread of 1.2 feet in the surface foot. The entire root system was much more profoundly branched than

was that of wheat grown at Lincoln. The primary laterals varied in length from 0.3 to 3.0 inches, frequently as many as 20 to 27 branches occurring on a single inch. Secondary laterals, 0.2 to about 0.5 inch in length, were numerous. Even the root-ends were well-branched with rather long laterals (fig. 27). Thus the root system, although largely confined to the surface 2 feet of soil, because of its wide lateral spread and profuse branching, was well adapted to extract water and solutes from these soils of low water-content. The roots in the surface 6 or 8 inches were not at all fleshy, but tough and wiry, and many were at this time drying out.

A final examination of wheat was made on July 7, when the plants were 83 days old. They had fully headed out by June 25, and were now in the dough stage. The crop averaged 1.7 feet in height, with a maximum height of 1.8 feet. The plants were thin on the ground, and many had no tillers, while

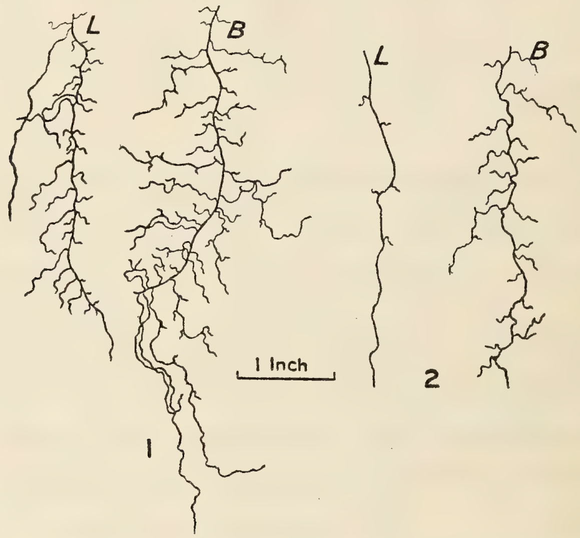


Fig. 27.—Wheat roots showing normal differences in branching at Lincoln, L, and Burlington, B. 1, at depth of 1.5 feet; 2, root-ends.

some showed 4 to 6 tillers, but the average total number of stalks in selected meter quadrats was only 201. Most of these did not head out (plate 2 A). When harvested on July 19, the heads were well filled and the grain was of fair quality.

The interval since the last examination on June 12 was one of scant water-supply and high evaporation. Rain fell on 11 days, but only 4 showers of more than 0.2 inch occurred, heavy rains falling on June 18 (1.35 inches) and on July 5 (0.45 inch). A glance at the water-content of the soil given in table 17 is sufficient to show the prevailing drought. During the latter part of the period the crops ripened and dried rapidly. Three days after the 0.45-inch rain, on July 5, no water was available in the surface 2 feet of soil. Although samples for water-content determinations were taken as usual in duplicate, local differences in soil-structure caused rather noticeable differences in run-off and penetration in closely adjacent areas in the same

level plat, so that a variation of 1 or 2 per cent of moisture was not uncommon. This variation probably accounts for the water-content apparently being exhausted below the hygroscopic coefficient. It seems, however, that crop plants growing in these more arid soils have a greater ability to more thoroughly exhaust the water-supply than when grown in more humid regions. This is due possibly to the development of greater osmotic pressure, and certainly to a more thorough occupancy of the soil area by roots. The latter establishes a closer relation to all available soil-moisture, an exceedingly important condition at a time when the soil becomes so dry that all capillary movement of water ceases.

The soil-temperatures during the period were high. The average daily temperature ranged from 65° (minimum 57°) to 76° F. (maximum 85° F., fig. 28). The average daily temperatures of the surface 6 inches of soil were

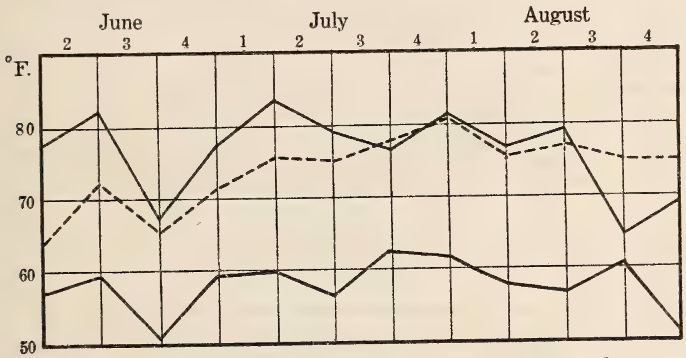


Fig. 28.—Average day and average night air-temperatures and average daily soil-temperature (broken line), Burlington, 1920.

4° to 7° F. higher after the first week of July than those at Lincoln. This was undoubtedly due to the drier and more insolated soil, for at Lincoln both day and night temperatures of the air averaged higher than those at Burlington. At Burlington the air-temperature ranged from 67° to 84° F. by day (maximum 99° F.) and 51° to 60° F. (minimum 43° F.) by night. Soil-temperatures at depths of 1 to 4 feet were about the same at both stations. Owing to the lag of soil-temperature (at 6 inches depth) at all stations, both in reaching a maximum (about 6 p. m.) and a minimum (about 7 a. m.), the day and night averages at any station were very nearly the same. The great range of air-temperatures from day to night (usually 35° to 45° F.) is significant, for high daily temperatures coupled with low humidity accentuate drought conditions, causing partial wilting and cessation of photosynthesis and growth. However, at night conditions are reversed and plants usually have opportunity to readjust their water-equilibrium. In fact, the average nightly humidity (79 to 90 per cent), which is caused largely by the low temperature, was greater than that at Lincoln. However, the average daily air-moisture (39 to 53 per cent) was much less (fig. 29). Not infrequently the hygrograph registered as low as 17 to 25 per cent.

It should be pointed out that the season of 1920 was one unusually favorable for crop development. On several occasions fogs were noted which did not clear away until the middle of the forenoon. Such atmospheric con-

ditions are very favorable for the conservation of water by plants. During these periods the wind, an important ecological factor, was still or of low velocity. Normally it is quite pronounced, averaging 130 to 160 miles per day and two to four or more times this amount during very windy weather. It plays an important part in desiccating both plants and soil. Throughout the period the evaporating power of the air ranged from 23 to 39 c. c. daily (table 18). Owing to the cool nights, which cause a rise in humidity, coupled

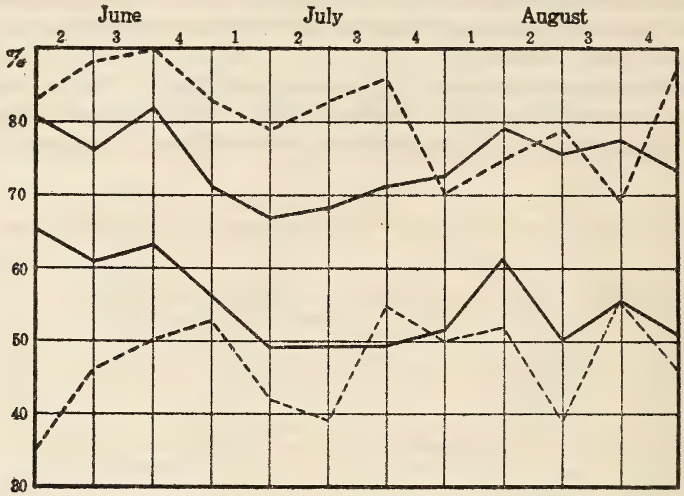


FIG. 29.—Average day humidity (lower lines) and average night humidity (upper lines) at Lincoln (solid lines) and Burlington (broken lines), 1920.

with the lesser wind movement, the evaporating power of the air is low. For example, from June 28 to 30, 1921, with typical clear, hot days and cool nights, the average day evaporation (6 a. m. to 6 p. m.) was 48 c. c. with 104 miles of wind, while the average night evaporation was only 10 c. c. with 51 miles of wind. Thus 83 per cent of the evaporation occurred during the day period. The conditions of low available water, high soil and air temperatures, es-

TABLE 18.—*Average daily evaporation at Burlington, 1920.*

	c. c.		*c. c.*
June 3 to 11	46.9	July 15 to 20	31.8
June 11 to 18	34.8	July 20 to 27	44.2
June 18 to 25	22.4	July 27 to Aug. 5	26.0
June 25 to July 2	38.4	Aug. 5 to 15	24.2
July 2 to 8	38.6	Aug. 15 to 18	59.8
July 8 to 15	42.1	Aug. 18 to 25	22.6

pecially by day, combined with great wind movements and low humidity, caused not only a dwarfing of the above-ground plant parts, but resulted in an extensive development of the root systems.

The wheat roots were very abundant to the depth of the hardpan, 2.7 feet. This dry layer determined the maximum penetration, which had not increased since the last examination, although the working depth was now only a little less than the maximum. Likewise, the lateral spread had

increased but slightly. Although the soil was very hard and dry and was removed with exceedingly great difficulty, it could be plainly seen that the wonderfully developed roots thoroughly occupied every cubic inch where available water was present.

Oats, Avena sativa.

Oats were also examined on June 12. The crop had an average height of 10 inches, although some plants were 13 inches tall. The tillering was not heavy; 2 or 3 tillers was an average number, while very rarely more than 5 occurred. Young tillers were infrequent. While the crop was in fairly

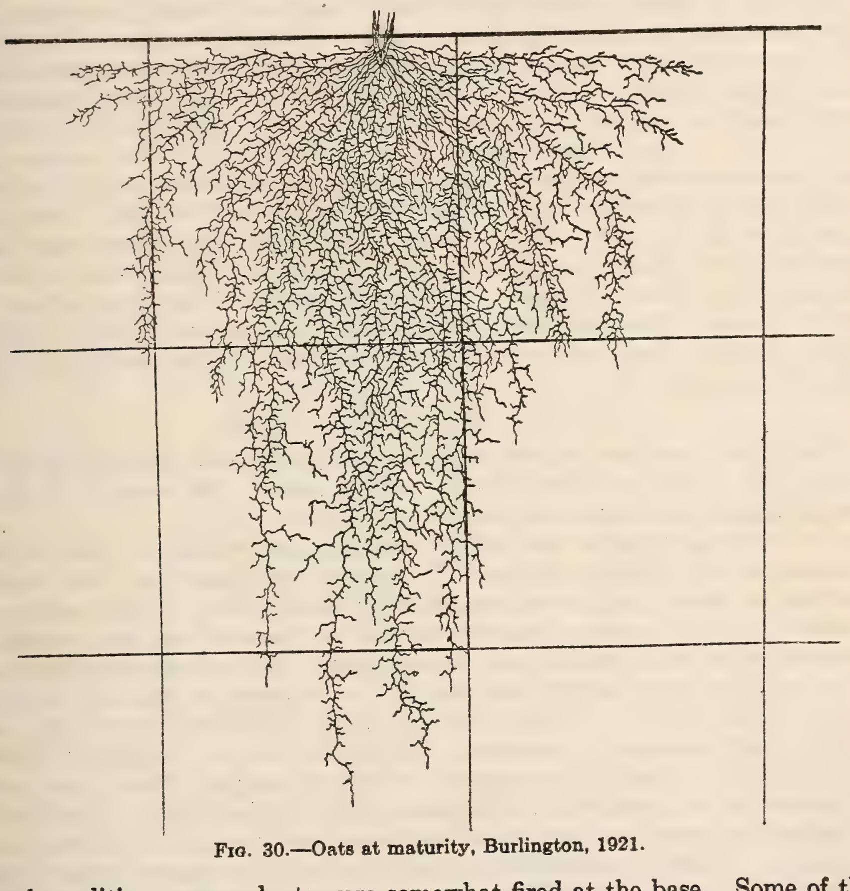


Fig. 30.—Oats at maturity, Burlington, 1921.

good condition, many plants were somewhat fired at the base. Some of the older leaf-tips showed effects of frost injury. As a result of the drought the leaves were more or less rolled, but scarcely to the extent of those of wheat or barley, some of which did not become turgid at night.

Some of the longest roots extended to a depth of 2.4 feet where very dry soil occurred. The working depth was the same as for wheat, 1.3 feet. The root habit, as regards surface lateral spread, abundance of roots at all angles to the vertical, and profound branching to the very root-ends, was very similar to that of wheat, but of slightly less degree in every respect.

This may have been due in part to the smaller number of plants supported by the oat roots. Compared with growth in more humid regions, the roots, while less extensive, were much more profoundly branched. Many young roots which had originated near the surface and were densely woolly with root-hairs, had dried out and died after reaching a length of only 0.3 to 3 inches. This fact leads one to believe that the excellent development of long, rebranched laterals, especially in the surface 1.5 feet of soil, may be correlated not only with the prevailing relatively low water-content, but also with the lack of ability on the part of the plant to produce new absorbing organs in the dry surface-soils.

On July 7, when the oats had reached a height of 1.5 feet (maximum 1.8 feet) and were in the dough stage, roots were again examined. The crop had been somewhat damaged by grasshoppers, but the grain was well filled and of good quality when harvested July 19. In making the excavation preliminary to root study, a very dry hardpan was encountered at a depth of 2.7 feet. It had a thickness of about 1.3 feet. Below this stratum the soil was mellow and powdery. Roots were quite abundant to the hardpan layer, and the working depth reached approximately this level. As in the case of wheat, the surface soil was also completely filled with exceedingly well branched roots, these apparently being a response to available water-content furnished by summer showers. The lateral spread of roots was about 10 to 11 inches. This root habit is markedly different from that of plants grown from the same seed in more moist soil and in a less arid climate (*cf.* figs. 21 A and 30).

Barley, Hordeum vulgare.

Barley was examined also on June 12. The plants were about 11 inches in height, the tallest exceeding this by only 2 inches. The number of tillers varied from 2 to 6 and averaged 3 or 4 per plant.

The working depth of the barley roots was determined at 2 feet; a few penetrated 4 to 6 inches deeper. The general root habit was very similar to that of wheat, the lateral spread being slightly less. In the surface 6 inches of soil the primary branches were 2 to 3 inches long, the secondary ones 0.3 to 0.5 inch, and all were densely hairy. On one root, at a depth of 4 inches, 58 primary laterals were counted on a segment of root only 2 inches long. These had an average length of about 1 inch and were fairly well supplied with secondary branchlets. On another root, at a depth of 5 inches, 26 branches occurred on a segment an inch in length. These cases well illustrate the profound root development in the first foot of soil. As already described for wheat and oats, numerous young roots from 0.3 to 3 inches long had died. These superficial roots must have had their origin during a time when moist soil prevailed; they were densely covered with root-hairs. As a whole, barley roots, like those of oats, are scarcely as well-developed as are those of wheat.

By June 25 the barley was nearly all headed out. The crop was somewhat damaged by grasshoppers. On July 7, when the root system was again studied, it was in the dough stage. The plants averaged 1.7 feet in height, with a maximum height of 2 feet. An average of 254 stalks were counted in selected square meters. The tillers averaged only one per plant, many having dried out and died. The roots extended even more widely in the

surface foot than those of wheat. Great mats of branches occurred in the surface 6 to 12 inches of soil, forming a profoundly developed absorbing system on all sides of the plant, even to a distance of 1 to 1.2 feet. The working depth was about 2.5 feet, while some roots reached a maximum of 2.9 feet, where they encountered the very dry hardpan.

Alfalfa, Medicago sativa.

Alfalfa was sowed at Burlington at the same time as the cereals already described, on April 15. On June 11, when the roots were examined, the plants were about 4.5 inches high, although the tallest ones reached 6 inches. The stand was quite good, and the plants had a normal green color, but some wilted badly during the hottest part of the day. Hardpan occurred in this plat at 2.2 feet depth. While the surface 6 inches of soil was very dry, below this a small amount of available water occurred to the hardpan layer (table 17). Most of the roots were about 1.7 feet deep, although some were traced

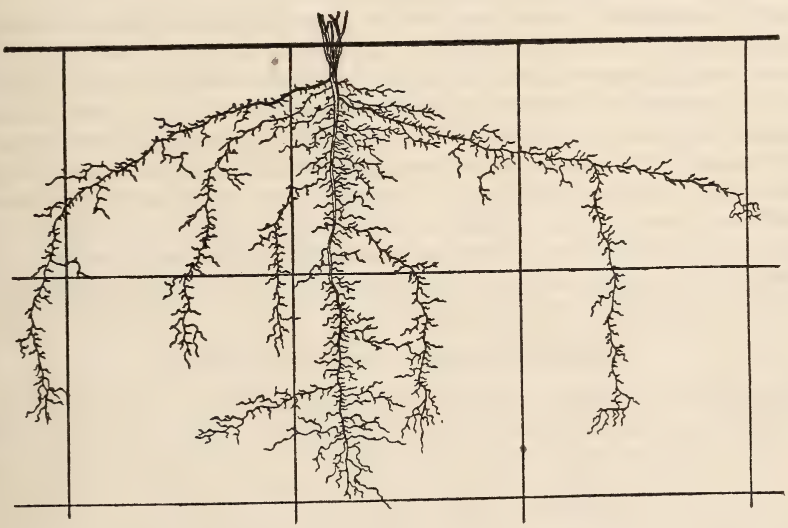


Fig. 31.—Alfalfa excavated at Burlington, June 28, 1921, during the second year of growth.

to 2.3 feet. The root habit, especially in the surface soil, was quite like that described at Lincoln, but in the deeper layers the roots were found to be more abundantly branched. Moreover, the branches were longer and extended nearer the root-ends.

A second examination was made on July 7, when the crop was about 5 inches high. Considerable variation in the development of the plants was noticeable, however, many being much smaller than the average and a few 8 inches tall. The trench was only a few feet from the preceding and the hardpan occurred at 2.1 to 2.3 feet depth. The soil, and especially the surface 8 inches, was very dry. Roots were abundant to the hardpan layer, but none extended beyond. They were characterized by a much more profuse branching than was found at Lincoln, and the lateral spread was also much greater. Undoubtedly this root habit is an adaptation to secure

the necessary supply of water, which occurred in limited amounts and was confined here to the surface 2 or 2.3 feet of soil. Chemical analyses (table 16) show that the soil is rich in all the necessary nutrients. Nodules occurred on the roots at all levels. Aeration could not have been a limiting factor to growth in this dry soil, and undoubtedly water played the dominant rôle. This conclusion is substantiated by further studies.

A final examination was made on August 25. The water-content (table 17) was rather uniformly low; however, determinations were made only at rather long intervals. Showers of 0.86 inch occurred July 16 and 17; 1.26 inches of rain fell on July 26; and 1.34 inches early in August; while a drought period of 15 days' duration was broken by 0.72 inch of rainfall on August 20. Although the crop was often in a semiwilted or wilted condition during the periods of stress (figs. 28 and 29 and table 18), when more favorable conditions occurred growth was resumed. Thus, by August 25 the plants had increased 6 inches in height since July 7, the tallest reaching 11 inches. They had blossomed and most of the flowers had dried.

In the new trench, which was not far from the former ones, the hardpan came to within 2 feet of the surface. This layer delimited the depth of root penetration and none was found deeper. The tap-roots were 3 or 4 mm. or less in diameter. They were profusely branched with both large and small laterals. Not infrequently some of the laterals were equal in size to the tap. Many spread at various depths almost parallel with the soil surface or obliqued downward, reaching distances of 1 to 1.5 feet, horizontally from the tap. Some were found with a maximum lateral spread of 1.5 to 2 feet. Small branches were numerous. The soil was remarkably well occupied by the network of roots, a condition quite unusual in fields of young alfalfa of more humid regions (*cf.* figs. 25 A and 31).

Sweet Clover, Melilotus alba.

The first examination of the root development of sweet clover was made on June 11, when the plants were 57 days old. They averaged 3 inches in height, although some were an inch taller. The stand was quite good. The tops were beginning to branch and the crop was in fairly good condition, except, as a result of drought, many of the leaves on some plants were partly wilted and folded during the hotter portion of the day. Not a few of the roots reached a maximum depth of 2.3 feet, and one, following the course of a large decayed Sudan-grass root, penetrated a foot deeper. The working depth was about 2.0 feet. The roots were mostly much smaller in diameter, especially in the dry surface 6 inches of soil, than those at Lincoln, but the root development as regards number, branching, and lateral spread was almost identical with the latter. In the deeper soil, however, branching was much better developed. Considerable variation occurred in regard to abundance of laterals near the tip. On some plants as many as 15 branches about 0.2 inch long occurred on a single inch of tap-root, while on others they were scarce. Numerous counts as regards number of primary and secondary branches showed that they were not only more abundant, but also averaged longer than those in the more humid soil eastward.

By July 7 the crop had reached a height of about 5 inches, although some especially well-developed plants were 8 inches tall. The more thrifty appear-

ance of the crop when compared with the plat of alfalfa was undoubtedly due in part to the greater depth of moist soil. In the portion of the sweet-clover field examined, the hardpan was 6 to 8 inches deeper than in the portion of the alfalfa field where roots were excavated. Except for rare cases of roots entering burrows, etc., none extended to depths greater than 2.8 feet, where hard, dry soil occurred. However, most of the roots reached this depth. As with alfalfa, they were furnished both with more numerous and longer laterals than were those at Lincoln. In the first foot of soil the laterals were often more superficial in position, a response no doubt due to the stimulus of moisture in the superficial layers and its dearth at lower levels. The tap-root branched profusely throughout its length almost to its very tip. Tubercles were abundant, often occurring in large clusters.

On August 25, when a final exmination was made, a long trench was dug in such a manner that while one end extended in heretofore undisturbed soil, the other reached into the territory of the former trench. As usual, the old trench had been sunk a foot or two below the deepest roots, and this one had been deepened still further (to about 6 feet) in order to examine the subsoil. It had been refilled with the mixed soil and subsoil. A marked difference in growth and vigor of the plants growing adjacent to the old trench and those in the undisturbed area was noted. While those in the latter area were only about 1 foot tall, the others were 1.3 feet high, more branched, and of better color. Where the dry, hardpan layer occurred at 2.7 feet depth, root penetration was limited to the soil above this layer. In general, the root habit was very similar to that of the alfalfa already described, the number of branches, their greater lateral extent and degree of rebranching being quite unlike plants from the same lot of seed grown in the moist soil at Lincoln. However, the plants growing at the sides of the old trench had extended their roots into the loose soil, which had been fairly well moistened, due to heavy rains, and, undoubtedly, to the entrance of run-off water from the surrounding area. Here a few roots were traced to depths of 6.8 feet, while many extended into the fifth and sixth foot of soil. In this new soil area the root development was similar to that described for plants at Lincoln.

Summary of Crop Development.

Crops grown at Burlington, Colorado, were, owing to the unfavorable climatic conditions, thin of stand, and the above-ground parts much dwarfed. Oats when mature averaged only 1.5, and wheat and barley 1.7 feet in height respectively. Root-depth was limited by water penetration and did not exceed 2.9 feet. Alfalfa and sweet clover, when 132 days old on August 25, were only a foot high and rooted entirely in the surface 2 to 2.7 feet of soil. Early spring environment, except for the low temperatures (especially at night), was quite favorable to crop growth. The cereals tillered freely and because of the rich soil all the crops grew quite too luxuriantly to successfully endure the drought conditions of June and later summer. Because of low water-content of both air and soil, all of the crops were from time to time in a semiwilted condition. Many tillers from the cereals died, as did also new roots put forth during intervals when the surface soil was moist. The extraordinary development of long, widely spreading, and profusely branching laterals, which thoroughly filled the soil above the hardpan layer

(at 2 to 2.7 feet), gave the plants a root development quite out of proportion to the tops and markedly different from those of more moist soil. This root development agrees with earlier studies of cereal crops, including winter-grown varieties, and in many respects with that of the native vegetation of the short-grass plains (*cf.* Weaver, 1920).

Summary of Environment and Crop Development at All Stations, 1920.

The stations at Lincoln, in southeastern Nebraska, Phillipsburg, in north-central Kansas, and Burlington, in eastern Colorado, are at altitudes of 1,100, 1,935, and 4,160 feet respectively. The vegetational expression of the climate at the three stations respectively are true-prairie, mixed-prairie, and short-grass plains. The precipitation for the growing-season, which begins 2 to 4 weeks later at the higher elevation, is shown for each station in figure 32, where the mean precipitation is also included. An examina-

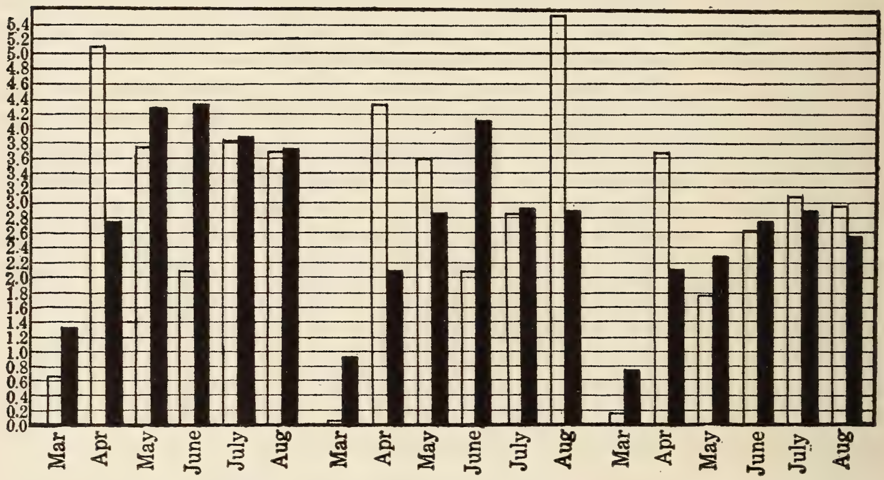


Fig. 32.—Mean precipitation in inches (black) and precipitation for 1920 at Lincoln (left), Phillipsburg, and Burlington.

tion of this figure shows that the rainfall at all stations during March was far below normal, but approximately twice normal during April, when the crops were planted. Aside from a deficiency of nearly half the normal rainfall at Lincoln and Phillipsburg during June, and an increase to twice the normal at the latter station during August, no marked irregularities in the precipitation occurred. The total precipitation at Lincoln during the period was 18.8 inches, which was only 0.3 inch greater than that of Phillipsburg. The precipitation at Burlington was about 75 per cent as great, but owing to numerous light showers and great run-off during heavy ones, its actual efficiency in increasing water-content of the soil was probably only half as great as the number indicates.

The soil at the Lincoln station consists of a fine-textured silt loam underlaid with clay loess. At Phillipsburg the mellow silt loam gives way at a depth of about 1 foot to a very mellow loess subsoil. The very compact silt

loam at Burlington is underlaid at about 2.5 feet with hardpan, while powdery loess occurs below this level. All of the soils are very fertile, their physical effect upon the water-content affecting crop production to a far greater degree than their chemical composition.

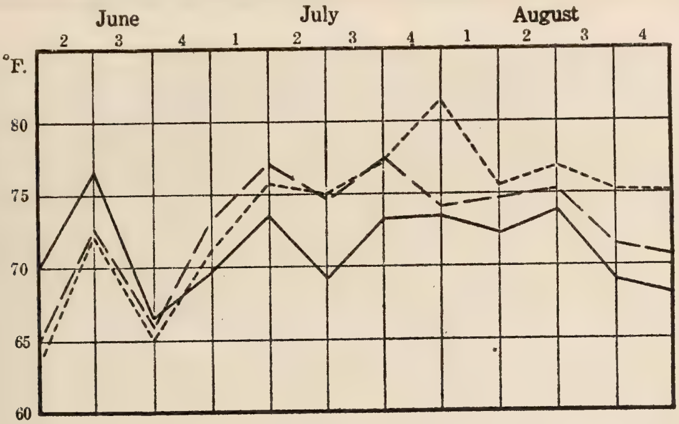


Fig. 33.—Average daily soil-temperature at Lincoln (solid line), Phillipsburg (long broken lines), and Burlington (short broken lines), 1920.

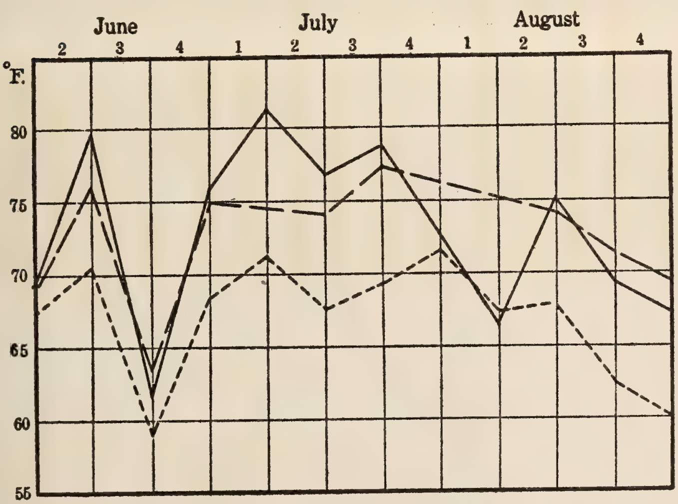


Fig. 34.—Average daily air-temperature at Lincoln (solid line), Phillipsburg (long broken lines), and Burlington (short broken lines), 1920.

A study of the water-content to a depth of 4 feet shows that at both the upland and lowland stations at Lincoln at least 7 per cent (and usually 10 to 20 per cent) available watei was present at all depths below 6 inches until the middle of July. At no time during the growing-season was the supply of available water, even in the surface 6 inches, entirely exhausted, a margin of 4 to 9 per cent being maintained in the deeper soil even during the driest part of the season. At Phillipsbuig the water relations were less favorable.

On July 1 no water was available in the surface 6 inches of soil, a week later only 1 or 2 per cent was available from 1 to 3 feet, while by the latter part of the month a deficit occurred to 2 feet and less than 1 per cent was available to 4 feet. Somewhat similar conditions prevailed late in August. Water relations at Burlington were even less favorable for plant growth than those

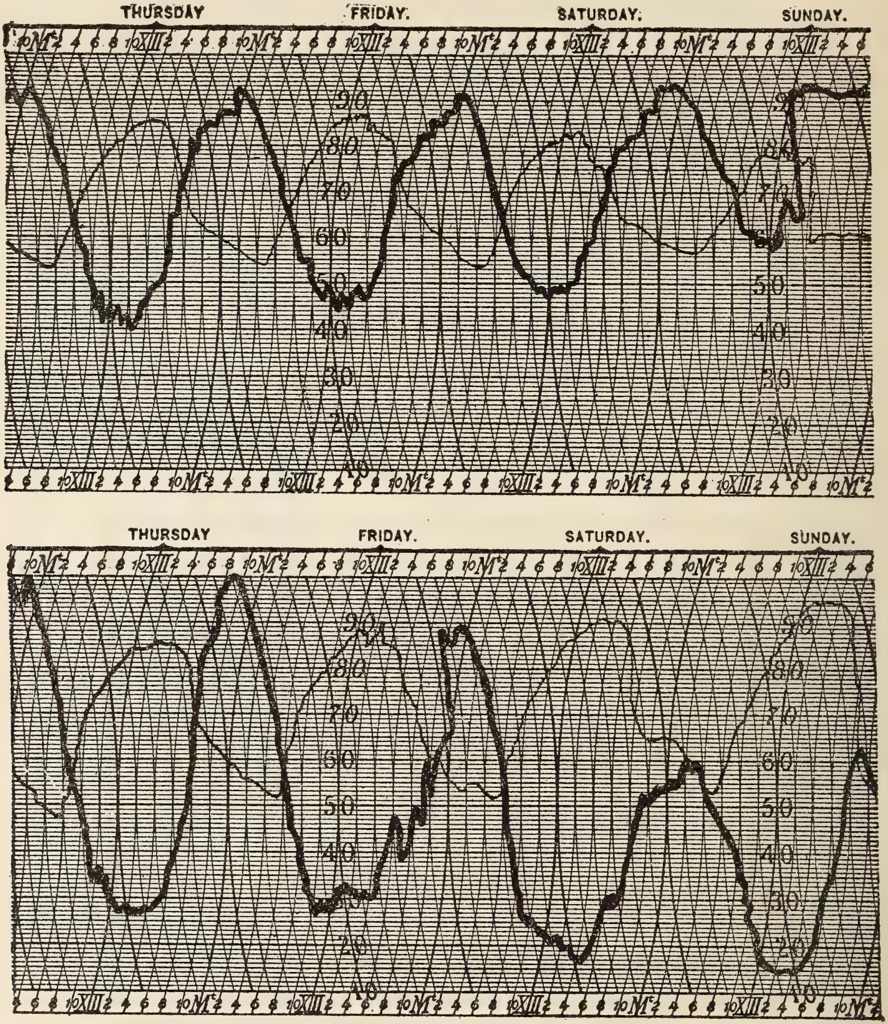


Fig. 35.—Hygrothermograph records from Lincoln (upper) and Burlington, June, 1921; light lines temperature, heavy lines humidity.

at Phillipsburg. While the surface foot was well moist during April, May, and early in June, only a small available supply (0 to 5 per cent) occurred in the second and third foot, while at no time during the season was the soil moist below the hardpan layer (about 2.7 feet deep). An available supply of only 1 to 6 per cent was found at all levels above the hardpan throughout

June, while during the remainder of the season a deficiency at all levels was not uncommon.

Soil temperatures at a depth of 6 inches were highest at Lincoln (70° to 77° F.), and lowest at Burlington (64° to 72° F.) during the first half of June, but by the last week in June this relation was reversed, the soil at Burlington remaining warmest throughout the season. The average weekly differences were often 6° to 8° F., the Lincoln soil being coldest, that at Phillipsburg intermediate, while the dry soils at Burlington had the highest temperature (fig. 33).

The average daily air-temperature throughout the season was usually 5° to 7° F. colder at Burlington than at Phillipsburg, while that at Lincoln was generally higher than that at Phillispburg (fig. 34).

The average day humidity at Lincoln ranged between 49 and 65 per cent and was usually higher than that at Burlington. However, the average night humidity at Lincoln (67 to 82 per cent) was usually exceeded by that at

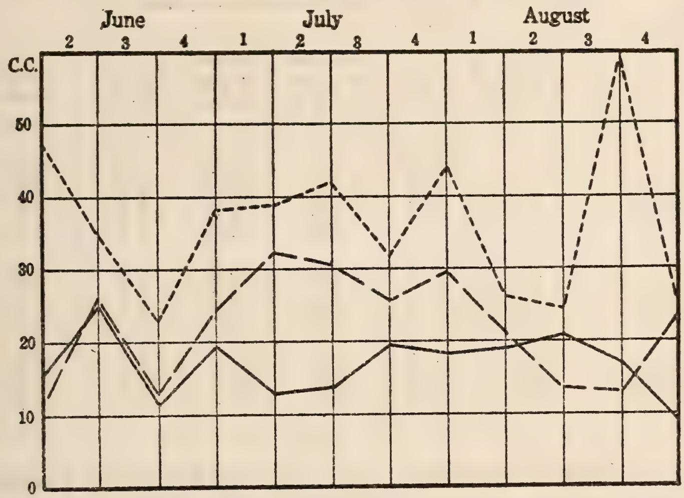


FIG. 36.—Average daily evaporation at Lincoln (solid line), Phillipsburg (long broken lines), and Burlington (short broken lines), 1920.

Burlington by about 8 per cent until late in July (fig. 29). Conditions at Phillipsburg were intermediate. The much greater daily range of both temperature and humidity at the Burlington station when compared with that at Lincoln is shown in figure 35. This combination of high temperature and low humidity, which occurs rather regularly in the afternoons at Burlington, when coupled with dry soil, are conditions very unfavorable for plant-growth.

Wind movement is much greater at Burlington than at either of the other stations and is an important factor in desiccating both crops and soil. An average day velocity of 8 or 10 miles per hour (at a height of 0.5 meter) is quite usual, while periods lasting for several days when the velocity reaches 20 or 30 miles per hour are not uncommon. The amount of wind is less at Phillipsburg and much less at Lincoln (for example, 4 miles per hour average daily from July 13 to September 19, 1916 (*cf.* Weaver, 1919 : 23).

The evaporating power of the air, which integrates, to a certain degree, the factors of radiant energy, humidity, and wind movement, was greatest throughout the season (23 to 60 c. c. average daily evaporation) at Burlington, intermediate at Phillipsburg (11 to 32 c. c.), and least (9 to 25 c. c. at Lincoln (fig. 36).

Thus the conditions for crop-growth as regards rainfall, water-content of soil, temperature, humidity, wind, and evaporation were most favorable at Lincoln, intermediate at Phillipsburg, and least favorable at Burlington. These conditions are indicated by the native vegetation and borne out by the growth of crops.

The relative height of the mature oats and barley at the several stations is shown in plate 3 (*cf.* also, plate 2 B, for wheat). These plates also show the comparative yield from an average square meter; the bundle on the right was taken in every case from the lowland plats at Lincoln. In table 19 may

TABLE 19.—*Summary of cereal crop development, 1920.*

Crop and station.	Date of harvest.	Ave. height.	Ave. yield in grams per sq. m.	Weight of 1000 kernels.	Working depth.	Max. depth.	Max. lateral spread.
Oats:		*feet.*		*grams.*	*feet.*	*feet.*	*feet.*
Lincoln..........	July 12	3.0	706	20.1	2.8	4.8	0.8
Phillipsburg......	July 20	2.6	379	16.6	3.3	6.0	0.8
Burlington.......	July 19	1.5	175	16.2	2.7	2.7	0.9
Wheat:							
Lincoln..........	July 15	3.2	740	29.8	3.5	4.8	1.0
Phillipsburg......	July 20	2.3	322	9.1	3.0	5.8	1.0
Burlington.......	July 19	1.7	205	20.1	2.7	2.7	1.2
Barley:							
Lincoln..........	July 12	2.7	607	32.7	3.3	5.4	1.0
Phillipsburg......	July 17	2.4	407	14.7	3.3	6.7	1.0
Burlington.......	July 19	1.7	176	23.9	2.5	2.9	1.2

be found a summary of the height, yield, and root development of the cereals at the several stations. The yield is the average of 25 to 30 square-meter quadrats taken from the several plats at the three stations respectively, that from Lincoln being from the lower crop area. All of the crops were assembled in the botanical laboratories of the University of Nebraska and thoroughly air-dried before weighing. A study of the table shows that the crops are progressively shorter from Lincoln westward and that the average yield is also less. The results correlate well with those obtained during 1919, when data from a large number of fields in the different grassland associations were obtained (Weaver, 1920 : 123).

Regarding weight of threshed grain, Lincoln is highest in every case, and Burlington second except in the case of oats. The low yield at Phillipsburg was due in part to the rust epidemic.

Root development, as regards both working depth and maximum extent, is greatest in every case (except one) at Phillipsburg, although these depths average less than those found at Peru during 1919. The shortest roots occurred at Burlington, where the hardpan demarked at once the limit of water penetration and root extent. The greater root extent at Phillipsburg

than at most mixed-prairie stations (Weaver, 1920 : 122) is in agreement with results obtained the preceding year and is probably due to the unusually moist subsoil resulting from 11 inches of excess precipitation during 1919, coupled with rather arid above-ground environment during the growth of the crops. In general, the root habit of the cereals was very similar at Phillipsburg and Lincoln, but markedly different from those at Burlington, where the abundance of roots, branching, etc., was much more pronounced in the surface soils.

During July, and again in August, 400 alfalfa plants of average size were carefully selected at each of the stations, cut just below the crown, thoroughly air-dried in the laboratories in Lincoln, and the dry weight obtained. Similar collections of sweet clover were made, each one containing 300 plants (plate 4). The development of the leguminous crops is summarized in table 20, where

TABLE 20.—*Development of leguminous crops, 1920.*

Crop and station.	Date of cutting.	Ave. height.	Dry weight of 400 av. plants.	Max. depth.	Date of excavation.
Alfalfa:		*feet.*	*grams.*	*feet.*	
Lincoln	July 12	1.5	528	5.7	July 24
Phillipsburg	July 9	0.7	292	5.0	July 10
Burlington	July 8	0.4	122	[1]2.3	July 7
Sweet clover:					
Lincoln	July 12	2.0	[2]840	5.5	July 24
Phillipsburg	July 9	1.3	461	5.7	July 9
Burlington	July 8	0.4	213	2.8	July 7
Alfalfa:					
Lincoln	Aug. 9	1.8	739	5.9	Aug. 10
Phillipsburg	Aug. 4	1.2	601	...	....
Burlington	Aug. 5	0.6	214	[1]2.0	Aug. 25
Sweet clover:					
Lincoln	Aug. 9	2.5	[2]1,103	...	....
Phillipsburg	Aug. 4	1.7	869	...	....
Burlington	Aug. 5	0.8	323	2.7	Aug. 25

[1] Depth determined by hardpan.
[2] At each station 300 sweet clover plants were taken.

the data for Lincoln are from the lower crop plats. A study of the table shows that both the height-growth and dry weight, like that of the cereals, correlates directly with available water-content, being greatest at Lincoln and least at Burlington. Root penetration is greater for sweet clover at Phillipsburg, but less for Alfalfa than at Lincoln, while at Burlington the depth of penetration of both is only about half as great. Tap-roots with relatively few short branches characterized the root system at the two less arid stations, but at Burlington the abundance of large, profusely branched laterals above the hardpan was very pronounced.

V. INVESTIGATIONS AT ALL STATIONS IN 1921.

In order to further check the results on root development, crops were again grown at all the stations during 1921. These consisted of University No. 21 oats, Marquis Spring wheat, and Manchuria barley. At the Peru station, Early Ohio potatoes and Iowa Silver Mine corn were also grown.

The small cereals were planted in plats of 25 square meters each and at the same rate (which was somewhat greater than the preceding years, p. 41) at all stations, viz, oats 64, wheat 90, and barley 72 pounds per acre. The seed was from the same lot and the time of planting at the several stations was approximately the same (March 24 to 30).

Investigations at Peru, Nebraska.

The experimental plats at Peru were the same as those of the preceding year, the small cereals being planted on the land formerly occupied by corn. A good seed-bed was prepared, the seed sowed evenly, hoed in, and the plats leveled off with a rake. The plat for potatoes was prepared by spading the soil to a depth of 8 inches. The tubers, from which all but one bud had been excised, were planted in rows which were 3 feet apart. The pieces of tubers were placed 2 feet apart in the row and at a depth of 4 inches. The corn was level-planted on May 17 at a depth of 3.5 inches after the plat had been spaded to a depth of 6 inches. The rows were 3 feet apart and the kernels were placed at intervals of 1.3 feet in the row. Both corn and potatoes were tilled with a hoe in such a manner as not to disturb the roots.

Owing to a deficiency in rainfall, coupled with poor distribution, the crops did not develop normally. At the time of harvest, about June 30, the oats averaged 2.4 feet in height; the crop, though evenly developed, was thin, having tillered so poorly that many single stalks occurred, while many others had but one or two tillers. However, the grain was well filled. The stand of barley was even thinner, single stalks being numerous and few plants having the usual numbers of tillers. Barley averaged 2.4 feet in height and had well-filled heads. Wheat was the poorest. The crop was very thin and uneven in development; more single stalks occurred than those with tillers. It varied in height from 1.6 to 2.8 feet, with an average of about 2 feet. The heads were small and only partly filled. Compared with 1919, also a drought year, oats and wheat were 7 or 8 inches shorter in average height, but the barley slightly taller. The stand was thinner in every case.

An examination of the rainfall and soil-moisture records makes clear the degree of drought. The rainfall during April was only 1.79 inches, over 70 per cent of which fell at one period (April 13 to 16). The rainfall for May, 3.07 inches, was 1.56 inches below normal and also poorly distributed, 72 per cent falling on May 7 to 10. June,[1] with 3.35 inches of precipitation, practically all of which occurred befoıe the middle of the month, had a deficiency of 1.38 inches.

The available water-content of the soil in the oat plat and also in a check plat of similar size kept free from all vegetation, is given in table 21. The relatively low water-content at the time of planting, and especially during June, is quite unusual for this station (*cf.* fig. 12). Table 21 indicates that

[1] Record from rain-gage installed at Peru; other records from Nebraska City.

by April 25 root activity was confined largely to the first foot or two of soil, while on June 10 the oats plat was much drier to 4 feet than the control. It should be stated in this connection that the potatoes did not exhaust the

TABLE 21.—*Water-content in excess of hygroscopic coefficient, Peru, 1921.*

Date.	Depth in feet.				
	0 to 0.5	0.5 to 1	1 to 2	2 to 3	3 to 4
Mar. 25, control	7.2	10.3	10.9	5.5	....
Apr. 12, oats	9.5	14.3	14.9	9.4	....
Apr. 25, control	15.2	17.3	15.0	11.7	....
oats	13.6	16.4	16.2	11.3	....
Apr. 30, oats	10.7	16.3	15.6	10.5	4.7
May 10, oats	22.5	21.3	19.9	15.0	....
May 21, oats	6.6	12.4	14.2	12.4	11.7
June 10, control	10.7	12.7	12.9	11.9	10.0
oats	5.7	4.3	5.6	6.3	4.7
June 25, oats	0.5	2.1	3.0	3.0	3.5
Hygroscopic coefficient	8.9	9.1	8.9	8.8	9.2

soil-moisture in any degree comparable with that of the oats. The potato plats on June 25 had 2.5 to 10 per cent more available water-content than the oats.

The temperatures under which root growth occurred are given in table 22.

TABLE 22.—*Soil-temperatures at Peru, 1921.*

Date.	0.3 foot.	0.5 foot.	1 foot.	2 feet.	3 feet.	4 feet.
	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*
Apr. 12	20.5	16.0	15.0	13.0	12.5	....
Apr. 25	17.0	16.5	15.5	13.5	12.0	....
Apr. 30	11.0	12.5	13.0	12.5	11.5	10.5
May 10	20.0	16.5	15.0	14.0	13.5	....
May 21	28.5	22.5	20.0	18.0	15.5	14.0
June 10	29.5	25.5	23.0	21.0	19.5	18.0

The relative root development of the mature crops during 1921 is compared with that of 1919 in table 23.

From table 23 it may be seen that the oat roots penetrated more deeply than in 1919, which is the only exception to the smaller cereal crops being somewhat less deeply seated in 1921. These differences are probably due in part to the direct effect of soil-moisture upon root development, the deeper soils being less moist than during 1919, while the maximum amount of water occurred at 1 to 3 feet. It seems probable, also, that there is some correlation between the development of the above-ground parts, which were poorer during 1921, and root extent. It has been pointed out that the oats made the best aerial growth of all the smaller cereals. The only differences in general root habit of these cereals from those grown in 1919 were a less marked development of the roots into a superficial and a deeply penetrating portion and the fact that root-hairs were much more abundant on the root-ends in the drier soils of 1921.

The potatoes examined had 53 and 60 roots respectively. The horizontal spread of the roots in the earlier stages of growth was very marked. The tendency of these roots to turn rather vertically downward at a later period was not so great during 1921; perhaps not more than 30 per cent of the roots penetrated far beyond the 1.5 to 2 foot level. At the time of examination (June 25) the soil-level with the maximum water-content occurred at 1 to 2 feet, the soil being drier both above and below this depth. This may account for the root behavior. The root-ends were much more branched than in 1919. In all other respects the root habit of potatoes was similar to that described (*cf.* fig. 11).

TABLE 23.—*Relative development of crops at Peru, 1919 and 1921.*

Crop and year.	Av. height.	Working depth.	Maximum depth.
	feet.	*feet.*	*feet.*
Oats:			
1919......	3.0	4.2	6.7
1921......	2.4	4.5	8.0
Barley:			
1919......	2.3	4.0	6.3
1921......	2.4	4.0	6.1
Wheat:			
1919......	2.7	4.3	6.7
1921......	2.0	4.0	6.6
Potatoes:			
1919......	2.3	3.2	4.7
1921......	2.0	2.8	4.3
Corn:			
1919......	8.5	6.0	8.2
1921......	8.5	6.2	8.3

The corn, although excavated on August 8, 83 days after planting, had reached practically the same extent as regards both height and root development as that excavated on September 2, 1919. In fact, the lateral spread of roots was 8 inches greater (4.7 feet) than in 1919. However, the last 6 or 8 inches of root-tips were still white and unbranched, indicating incomplete growth. The shallower roots were even more profoundly branched, with 18 to 20 laterals per inch, than those which penetrated deeper. In every way the root habit agreed with that described for 1919 (*cf.* fig. 9).

INVESTIGATIONS AT LINCOLN, PHILLIPSBURG, AND BURLINGTON.

The experimental plats at Lincoln during 1921 were on a level area of soil, the physical and chemical nature of which was almost identical with that of the lowland plats (*cf.* p. 40). Potatoes had been grown on the area the preceding year. A good seed-bed was formed by plowing and harrowing a few days before hoeing in the crops on March 24.

At Phillipsburg the crops were grown only a few meters from the 1920 plats; the preceding crop was barley. The soil was plowed about 5 inches deep and harrowed on March 24 and the crops hoed in the next day.

The crop plats at Burlington also adjoined those where roots had been dug the preceding year. The wheat and oats stubble had been plowed

about 6 inches deep early in November and a good seed-bed formed by repeated harrowing on March 30, just preceding hoeing in the crops. At this time, general farming operations had begun.

The soil at all the stations was in good tilth as regards soil-moisture at the time of seeding. Owing to a late spring, with severe freezes and snow, especially during the first half of April, the crops developed rather slowly, particularly those at the stations with the higher altitudes. The comparative development of the crops at the several stations on April 28 to 30 is shown in table 24. The precipitation during this period was 3.2 inches

TABLE 24.—*Crop development at the several stations, April 28 to 30, 1921.*

Crop and station.	Av. height, in inches.	Av. No. of leaves.	Av. No. of tillers.	Remarks.
Oats:				
Lincoln......	7	4	2.5	Stand good; crop evenly developed.
Phillipsburg..	3.5	3	2	Do.
Burlington...	1.75	1.5	0	Stand good; crop unevenly developed.
Wheat:				
Lincoln......	7	4	3	Stand good; crop evenly developed.
Phillipsburg..	4	3	2	Stand fair; crop evenly developed.
Burlington...	2	1.5	0	Stand good; crop unevenly developed.
Barley:				
Lincoln......	8	4	3	Stand good; crop evenly developed.
Phillipsburg..	4.5	3	2	Do.
Burlington...	2	1.5	0	Stand good; crop unevenly developed.

at Lincoln, 2.0 at Phillipsburg, and 3.9 at Burlington. However, at Lincoln this was distributed over 5 periods (where the rainfall was at least 0.23 inch), but at the other stations over only 2 periods. The great water-loss to the soil occasioned by high run-off, especially at the Great Plains stations, has already been discussed (p. 61).

Available water-content on April 28 to 30, to a depth of 4 feet, is shown in table 25. It may be noted at a glance that the soils at practically all

TABLE 25.—*Water-content in excess of the hygroscopic coefficient, 1921.*

Depth, in feet.	April 28 to 30.			May 19 to 21.			June 9 to 10.			June 22.		June 30, Burlington.
	Lincoln.	Phillipsburg.	Burlington.	Lincoln.	Phillipsburg.	Burlington.	Lincoln.	Phillipsburg.	Burlington.	Lincoln.	Phillipsburg.	
0 to 0.5....	15.6	13.9	11.2	11.9	13.1	6.6	17.5	20.7	2.7	7.6	1.0	−2.6
0.5 to 1....	16.5	12.3	9.7	15.7	12.2	7.4	16.2	14.9	1.9	9.4	5.1	−1.9
1 to 2.....	16.6	7.7	8.8	17.1	9.9	3.5	12.5	3.9	0.3	10.8	3.6	−2.1
2 to 3.....	15.9	2.7	2.4	14.9	5.4	[1]−0.7	12.9	4.3	[1]−0.4	10.2	1.0	[1]−1.0
3 to 4.....	14.0	3.6	0.9	14.7	5.2	0.2	13.9	5.2	−0.2	12.0	5.0	−1.3

[1] The fluctuations of soil-moisture at depths below 2.5 feet slightly above or below the hygroscopic coefficient are due largely to variations in the texture of the soil which occur even at the short distances apart at which the samples were taken, and not to actual changes in the water-content.

depths are progressively drier westward. Abundant moisture was present at all levels at Lincoln; the soil below 1 foot was quite dry at Phillipsburg, while no available moisture occurred below 3 feet at Burlington. However, at all stations the surface soil had been fairly moist during the period, and undoubtedly the limiting factor to growth was temperature.

At Lincoln the mean temperature for April was 53.9° F., at Phillipsburg 54.2°, and at Burlington 50.4°. The temperature at Lincoln fell below freezing on 6 days (latest April 17) during April, at Phillipsburg on 7 days (latest April 26), and at Burlington on 13 days, including April 28. The crops at the latter station had been damaged somewhat by frost. The soil-temperature to depths of 4 feet on April 28 to 30 are given in table 26. These

Table 26.—*Soil temperatures, 1921.*

Depth, in feet.	April 28 to 30.			May 19 to 21.			June 9 to 10.			June 22.		June 30, Burlington.
	Lincoln.	Phillipsburg.	Burlington.	Lincoln.	Phillipsburg.	Burlington.	Lincoln.	Phillipsburg.	Burlington.	Lincoln.	Phillipsburg.	
	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*
0 to 0.5....	15.4	24.0	12.0	21.0	20.0	22.2	22.5	21.4	19.8	21.2	23.2	29.2
0.5 to 1....	13.0	23.1	11.0	19.0	17.8	15.0	21.8	20.2	18.8	21.1	22.4	26.1
1 to 2.....	12.0	15.0	10.5	13.4	16.4	14.0	20.2	18.8	16.8	20.1	21.5	23.9
2 to 3.....	12.0	14.0	10.5	13.1	15.0	12.4	18.6	17.2	15.8	18.8	21.2	21.8
3 to 4.....	10.8	12.0	10.0	12.0	13.5	11.8	17.8	16.0	15.0	17.4	20.5	20.0

data show that the drier soils at Phillipsburg were warmer at all depths than those at Lincoln, while the Burlington soils were much colder than at either of the other stations.

By May 18 to 21 the wheat and barley at the several stations had reached the stages of development shown in plate 5. The condition of the oats in the various plats at this time is shown in plate 6. Judging from general crop conditions, the growing-season at Phillipsburg was at least a week later that than at Lincoln, while that at Burlington was perhaps 3 weeks later. A summary of crop development is given in table 27. At both Phillipsburg

Table 27.—*Crop development at the several stations, May 18 to 21, 1921.*

Crop and station.	Av. height, in inches.	Av. No. of leaves.	Av. No. of tillers.	Remarks.
Oats:				
Lincoln......	17	6	5	Thick, even growth.
Phillipsburg..	7	5	4	Crop thinner than at Lincoln.
Burlington...	3	4	2	Crop uniform but thin.
Wheat:				
Lincoln......	18	5	6	Thick, even growth.
Phillipsburg..	8	4	5	Crop uneven, thinner than at Lincoln.
Burlington...	3	3	3	Crop uniform but very thin.
Barley:				
Lincoln......	18	6	5	Thick, even growth.
Phillipsburg..	10	5	4	Crop thinner than at Lincoln.
Burlington...	3.5	4	2	Crop uniform but thin.

and Burlington the cereals, and particularly the oats and wheat, had many dead or injured leaf-tips, probably the result of local drought, coupled with frost injury at the latter station. At all the stations the development of the crops checked well with those in adjoining fields, respectively.

The precipitation during the period (April 28 to May 20) was 3.8, 2.2, and 0.7 inches going from Lincoln to the western stations, respectively. The available water-content on May 19 to 21 (table 25) occurred in decreasing amounts as one proceeded westward. In the first 2 feet of soil the minimum supply, which was 12 per cent at Lincoln, fell to 10 per cent at Phillipsburg

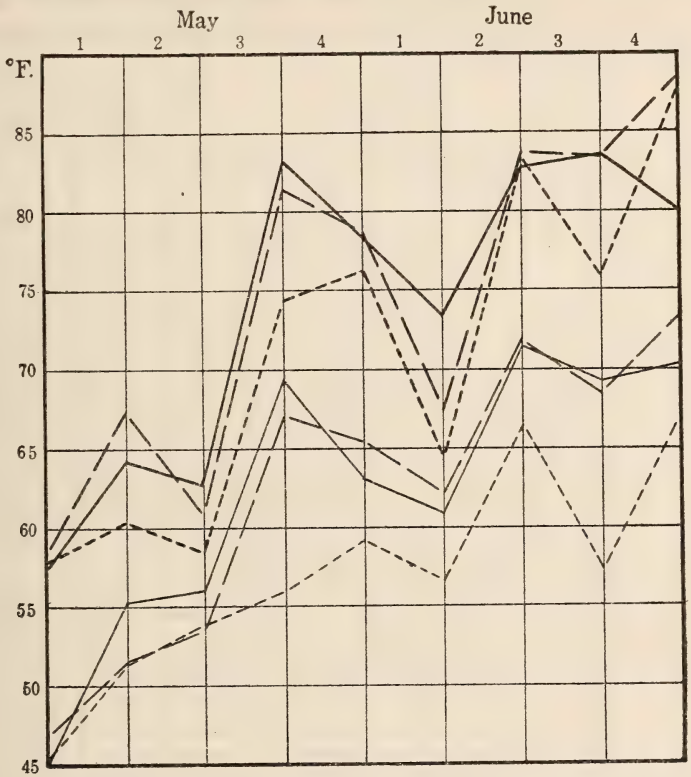


FIG. 37.—Average day air-temperatures (heavy lines) and average night temperatures (light lines) at Lincoln (solid lines), and Phillipsburg (long broken lines) and Burlington (short broken lines), 1921.

and 4 per cent at Burlington. At a depth of 2 to 4 feet no water was available at Burlington, about 5 per cent at Phillipsburg, and 15 per cent at Lincoln.

Soil-temperatures (except for fluctuations in the surface foot) had increased at all stations (table 26) and were more favorable for root development. A continuous record of the temperature at a depth of 3 inches in the prairie sod was obtained at Phillipsburg and Burlington. The average daily temperature at Phillipsburg varied from 55° to 60° F. while at Burlington it was rather consistently 5° colder. The daily range at Burlington (12° to 18° F.) was also somewhat greater than at the former station. The average day

and night air-temperatures during this interval are shown in figure 37. In general, the temperature is highest at Lincoln and lowest at Burlington. The low night temperature (45° to 56° F.) is especially significant in considering the growth of crops. The lower relative humidity and greater wind movement is indicated by the higher evaporation at Phillipsburg and Burlington (fig. 38).

On May 25, the barley at Lincoln began to head out. By the first of June all of the crops were fairly well headed and had an average height of 3 feet. The wheat and oats continued heading during the first week of June. The crops had been blown down badly on May 8 during a heavy rainstorm, but recovered more or less completely by June 1, when another storm lodged the wheat and barley again.

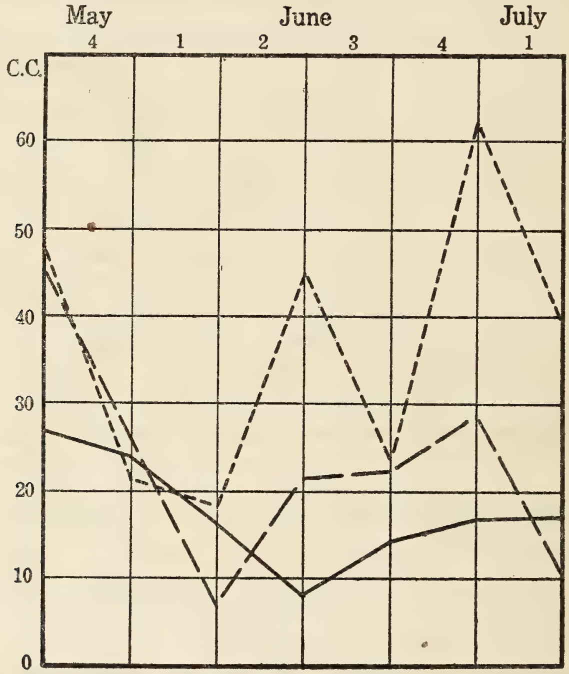


Fig. 38.—Average daily evaporation at Lincoln (solid line), Phillipsburg (long broken lines), and Burlington (short broken lines), 1921.

At Phillipsburg the crops headed out about a week later than at Lincoln. Moreover, they developed much more irregularly, the barley having an average height on June 10 of about 2.7 feet, the oats 2.3 feet, while the wheat was only 1.9 feet tall. The latter crop had been rather severely damaged by drought; all but the upper two or three leaves were badly discolored or dead.

At Burlington none of the cereals exceeded a foot in average height on June 10, and they did not begin heading out until 10 days later. The effect of a scant water-supply was shown by the many dry and dead leaf-tips, this being especially marked on the first four or five leaves. It is interesting to note that these shorter plants with less extensive foliage had almost as

many leaves as the taller ones at the other stations. Plate 7 shows the relative development of wheat and barley on June 10, while the oat plats at the several stations are shown in plate 8.

Rainfall during this period (May 20 to June 10) was 4.0, 5.7, and 1.7 inches at Lincoln, Phillipsburg, and Burlington, respectively. The water-content of the soil is given in table 25. The well-watered soil at all depths at Lincoln (13 per cent or more) contrasts strikingly with the drier subsoil at Phillipsburg (5 per cent or less); while at Burlington scarcely 2 per cent was available in the first foot and none deeper. However, during the intervening period (May 28), conditions were slightly better, with 4 to 7 per cent available moisture in the surface foot at Burlington, while moisture relations at Phillipsburg were similar to those indicated in the table. At no time at Lincoln was there a period of drought, well-distributed and ample rainfall keeping the soil moist.

The average soil-temperature at a depth of 3 inches was highest at Phillipsburg (68° to 72° F.), intermediate at Lincoln (66° to 68° F.), and lowest at Burlington (65° to 68° F.). The daily range at Burlington (16° to 20° F.) was slightly greater than at either of the other stations. After June 16 all of the soil thermograph-bulbs were placed at a depth of 18 inches. At this level the weekly fluctuations did not exceed 2° or 3° F., except in the drier soils at Burlington, where they were 4° or 5° F. At this depth the average weekly temperatures at Phillipsburg varied from 74° to 76° F. (June 16 to July 3), at Lincoln 70° to 72° F., and at Burlington 66° to 73° F. The temperatures at greater soil-depths are given in table 26. It seems clear from these data that differences in soil-temperatures at the several stations are so small that they exert little effect upon crop-growth, especially after the seedling stage has been past. Air-temperatures at all the stations were very much higher than during the preceding interval, but the same general relation with highest temperatures at Lincoln and the lowest at Burlington prevailed. An exception to this was the slightly warmer nights at Phillipsburg during a part of the period (fig. 37). Night temperatures at Burlington continued low (averages, 55° to 59° F.), the thermograph-pen sometimes falling to 42° F. The evaporating power of the air during the last week in May was practically the same (22 c. c.) at all the stations, but otherwise much higher, as usual, at Burlington (fig. 38).

The crops ripened at Lincoln and Phillipsburg at practically the same time. On June 22 and 23, when they were in the early dough stage, the barley alone being somewhat further advanced in development, the roots were examined and several representative meter-quadrats of each plat were harvested. The crops at Burlington, which were considerably damaged by grasshoppers, had reached a similar stage of development when they were harvested on June 30. The sheaves were shipped to Lincoln, where all were thoroughly air-dried in one of the University of Nebraska botanical laboratories, and finally weighed.

Rainfall at both Lincoln and Phillipsburg was light during this interval (0.4 inch or less). This is reflected in the water-content of the soil shown in table 25. In this connection it should be pointed out that even when the crops were mature the soil at a depth of 4 to 7 feet was very moist at Lincoln (18.5 per cent) and less so at Phillipsburg (11.1 per cent). This condition

is normal for eastern Nebraska (Weaver, 1920), while the moist subsoil at the latter station may have resulted from the heavy precipitation (11 inches above normal) during 1919. At Burlington a total of 2.3 inches of rain fell on June 18 to 21, but by June 30 no moisture was available for growth at any level (table 25).

Soil-temperatures were much higher during this period, especially in the drier soils at Phillipsburg and Burlington, where an increase of 4° or 5° F., even at depths of 3 or 4 feet, occurred. Air-temperatures remained relatively high, with the characteristic sequence of day and night temperatures for the several stations already noted (fig. 37). The great range of temperature and humidity at Burlington from day to night and the low night temperatures were not inducive to rapid growth. Average daily evaporation during the period ranged from 24 to 62 c. c. at Burlington, from 22 to 28 c. c. at Phillipsburg, while at Lincoln it varied from 8 to 17 c. c.

TABLE 28.—*Relative development of crops, 1921.*

Crop and station.	Ave. height.	Ave. No. stalks per sq. meter.	Ave. No. stalks per plant.	Ave. length of heads or panicles in inches.	Ave. No. of heads per sq. meter.	Ave. total weight dry matter per sq. meter.	Working depth.	Max. depth.
	feet.						*feet.*	*feet.*
Oats:								
Lincoln......	3.2	375	3.3	10.5	283	792	2.6	4.8
Phillipsburg..	2.8	353	2.9	9	269	366	3.0	5.3
Burlington...	1.5	[1]414	2.5	5	171	180	2.2	2.5
Wheat:								
Lincoln......	3.2	648	2.8	4	365	557	2.5	4.3
Phillipsburg..	2.6	475	1.8	3.5	211	314	2.7	4.5
Burlington...	1.6	[1]419	1.6	2.5	277	172	2.2	2.5
Barley:								
Lincoln......	3.1	384	3.7	[2]3.5	306	622	2.8	4.6
Phillipsburg..	2.8	253	2.2	3.25	201	369	3.1	6.0
Burlington...	1.3	[1]255	1.6	2	197	122	2.0	2.5

[1] Many stalks were only 2 to 4 inches tall and had been dead for some time.
[2] Average length of heads without awns.

Data on the development of the crops at the several stations at the time of harvest is given in table 28. An examination of table 28 shows in every case, as in 1920, a decrease in height of the crop from the more humid to the more arid stations. The same general relation holds for the average number of stalks per square meter, except at Burlington, where many tiny stalks, only 2 to 4 inches tall, started growth relatively early and soon dried out, but remained until harvest. During 1920 the average number of stalks per square meter at Burlington was from one-third to one-half less than at the other stations, although the number at Phillipsburg often exceeded that at Lincoln. The average number of stalks per plant (1921) was in direct relation to the water-content of soil and other factors favorable or unfavorable to plant-growth. In general, this relation held also during 1920. The average number of heads per square meter and the average length of heads or panicles decreased from Lincoln to Phillipsburg and Burlington respectively.

An exception to this occurred in the case of the number of heads of wheat at Burlington when compared with Phillipsburg, while the difference in this respect in the case of barley was small. However, a clear gradation in the reduction of total dry weight from east to west is apparent. Root extent, whether working depth or maximum penetration, is least at Burlington, intermediate at Lincoln, and greatest at Phillipsburg. As pointed out elsewhere (p. 76), the very deep root penetration at Phillipsburg is thought to be due to an unusually high water-content of the mellow loess soil and especially the deeper subsoil.

Summary of Environment and Crop Development.

The season of 1921 was one of drought at the Peru station. A deficiency of rainfall, coupled with poor distribution, resulted in a much drier soil than in 1919, especially the deeper subsoil. The stands of oats, wheat, and barley were thin, the plants having tillered poorly, and the height-growth, which

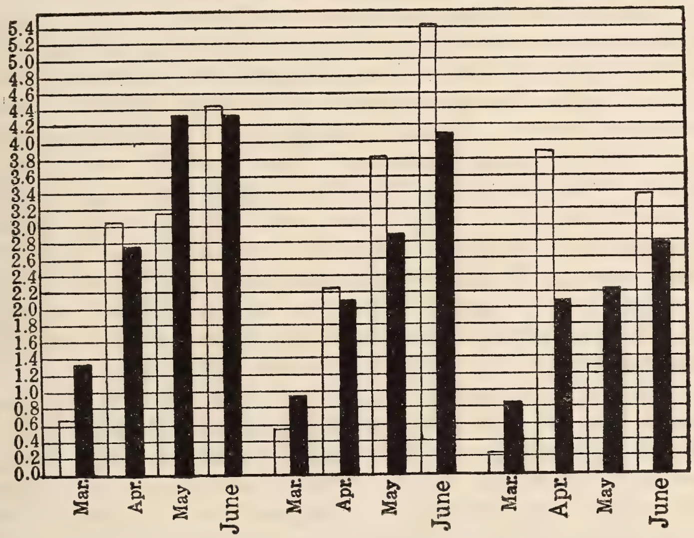


Fig. 39.—Mean precipitation in inches (black) and precipitation for 1921 at Lincoln (left), Phillipsburg, and Burlington.

varied from 2 to 2.4 feet, except in the case of barley, was 6 to 8 inches less than in 1919. The root systems, except in the case of oats, were somewhat less deeply seated than in 1919, reaching working depths of 4 feet and having a maximum depth of 6.1 to 6.6 feet. Oat roots were traced to depths of 8 feet. All of the smaller cereals showed a less marked development of the roots into a superficial and a deeply penetrating portion than in 1919. Potato roots, while very similar in distribution to those of 1919, showed a lesser tendency to turn downward at a later period in their development. This, like the lesser penetration of the roots of the cereals, may be due in part to the fact that the largest supply of available water occurred in the 1 to 3 foot level. Corn, although examined on August 8, had reached the same height (8.5 feet) and had approximately the same root depth as on September 2,

1919. The root habit was similar to that of 1919, except the lateral spread was 8 inches greater (4.7 feet).

Crops of oats, wheat, and barley were again grown at Lincoln, Phillipsburg, and Burlington during 1921, in order to check the results obtained at the several stations during the preceding year. The precipitation for the season (March to June inclusive) was 1.5 inches below the normal at Lincoln, 0.9 inch above at Burlington, and 2.0 inches above the normal at Phillipsburg. Precipitation for March was approximately half or less than half normal at all stations, but April was unusually wet, an excess of 1.8 inches occurring at Burlington. During May a deficiency of about an inch occurred at both Lincoln and Burlington, while Phillipsburg had an excess of an inch. During June 1.3 inches and 0.5 inch of rainfall above the normal occurred at Phillipsburg and Burlington respectively, while the rainfall at Lincoln was about normal (fig. 39). However, the rains at Lincoln were so well distributed that no drought period occurred, while at the other stations these were not infrequent, especially at Burlington, where much moisture fell in light showers or torrential rains. However, the season as a whole was favorable for crop-growth.

A study of the water-content to a depth of 4 feet (table 25) shows, with an occasional exception in the surface foot, a progressively drier soil from Lincoln westward. At no time during the growth of the crops was there a deficiency of soil-moisture at Lincoln. In fact, a margin of 7.5 to 16 per cent above the hygroscopic coefficient usually occurred. Less favorable conditions existed at Phillipsburg, where the subsoil (2 to 4 feet) at the time of planting had an available moisture-supply of only 3 per cent. This increased during May and June to 5 per cent, but was reduced by June 22 to 1 per cent at 3 feet in depth. The crops at Burlington had sufficient water above the hardpan (3 to 11 per cent) during April and May, but by June 10 this was reduced to about 3 per cent, and when the crops were ripe on June 30, no available water was present at any depth (*cf.* Briggs and Shantz, 1912 : 62).

Average daily soil-temperatures at a depth of 3 inches in the prairie sod ranged from 55° to 60° F. at Phillipsburg from April 28 until May 20 and about 5° F. lower at Burlington. From May 20 until June 16 the temperature was highest at Phillipsburg (68° to 72° F.), intermediate at Lincoln, and coldest (65° to 68° F.) at Burlington. Temperatures at a depth of 18 inches, after June 16, although quite constant at any station, were also about 6° F. lower at Burlington. This general relation held to a depth of 4 feet, although differences were so slight that, except in very early spring, they probably have little effect upon crop development (table 26). The average day air-temperatures (fig. 37) were, as during the preceding season, highest at Lincoln and lowest at Burlington, while this same general relation held for average night temperatures, those at Burlington varied from 45° to 67° F.

The average day humidity, in general, held the same relation as during 1920, viz, being much higher at Lincoln and lower at Burlington than at Phillipsburg. The extremes of temperature and humidity at Burlington were quite as pronounced as during 1920. The average daily evaporating power of the air at the several stations is shown in figure 38. At Burlington this sometimes reached a maximum of 45 to over 60 c. c., at Phillipsburg 28 to 45 c. c., while at Lincoln it did not exceed 18 to 27 c. c. Thus all of the environmental conditions for crop-growth were most favorable at Lincoln, intermediate at Phillipsburg, and least favorable at Burlington.

The relative development of the crops at the several stations at different periods of growth is shown in plates 5 to 8. A summary of crop development during 1921 is given in table 29, where the data of the preceding year are also included.

An examination of table 29 shows that the crops at Lincoln and Phillipsburg had as great, and in nearly every case a greater, height-growth in 1921 than during the preceding season. At Burlington the height-growth was the same for oats during the two years, but less for the other cereals in 1921. The average yield of dry matter at the several stations is not only in the same sequence as during 1920, but the relative amounts are strikingly similar. The working depth of roots is slightly less than during 1920, as is also, in general, the maximum depth of penetration.

Table 29.—*Comparison of crop development, 1920 and 1921.*

Crop and station.	Av. height, in feet.		Av. yield in grams per sq. meter.		Working depth, in feet.		Maximum depth, in feet.	
	1920	1921	1920	1921	1920	1921	1920	1921
Oats:								
Lincoln	3.0	3.2	706	792	2.8	2.6	4.8	4.8
Phillipsburg	2.6	2.8	379	366	3.3	3.0	6.0	5.3
Burlington	1.5	1.5	175	180	2.7	2.2	2.7	2.5
Wheat:								
Lincoln	3.2	3.2	740	557	3.5	2.5	4.8	4.3
Phillipsburg	2.3	2.6	322	314	3.0	2.7	5.8	4.5
Burlington	1.7	1.6	205	172	2.7	2.2	2.7	2.5
Barley:								
Lincoln	2.7	3.1	607	622	3.3	2.8	5.4	4.6
Phillipsburg	2.4	2.8	407	369	3.3	3.1	6.7	6.0
Burlington	1.7	1.3	176	122	2.5	2.0	2.9	2.5

Correlation of Crop Development with that of Native Vegetation.

Native plants have the same general requirements as regards heat, light, water, etc., as cultivated crops. Since their growth is controlled by the same physiological conditions, generally speaking, that hasten or retard the growth of crops, the use of the native vegetation as an indicator of the possibilities of crop production and as a criterion of average yield in a given plant association is patent. Different environments in agricultural regions should give, broadly speaking, similar differences in relative growth, yield, etc., of crop plants as of the native vegetation. Thus native plant-growth becomes a measure of the effect of all the conditions which are favorable or unfavorable for agriculture. Although conditions for growth, as indicated by a plant association, can be brought out with sufficient clearness to predict with a fair degree of certainty what will happen when crops are planted, the final test is the success or failure of the crop when grown (*cf.* Shantz, 1911). It is instructive, therefore, to consider the correlation between crop development and that of the native vegetation in the range of habitats under which these investigations were made.

The differences found in the lesser height-growth, smaller yield, and less extensive underground parts, going from the more mesophytic eastern stations to those of greater aridity westward, correlate directly in nearly every way with the growth of native vegetation, whether trees, weeds, or species of the native grass land are considered. The native vegetation growing through a long period of years integrates the climatic conditions during its growth. Thus it is not only an expression of the present conditions, as is true largely of rapidly maturing crops, but is to a large extent a record of conditions that have obtained during a period of many years.

The favorable climate for tree-growth at Peru is indicated not only by the large number of species present, but also by their development both in diameter and height. At Lincoln, forests are confined to the flood-plains. The species are much fewer in number and the trees are smaller both in diameter and height (*cf.* Pool, Weaver, and Jean, 1918). Only a very few species occur along the streams at Phillipsburg, and these are noticeably smaller in every way than those at Lincoln, while the few drought-enduring species which can grow only under cultivation on the plains at Burlington are even smaller of stature.

The variety and abundance of the weed flora of eastern Nebraska, as well as the rank growth of the plants, stand in striking contrast to the paucity of species, their lesser abundance, and poorer development at the western stations. Very marked differences occur even between Phillipsburg and Burlington, low water-content of soil, except in early spring, almost constantly inhibiting normal growth at the latter station. Such widely distributed species as *Grindelia squarrosa* and *Amaranthus retroflexus* reach heights of 3 or more feet in eastern Nebraska, but are often limited to a growth of 6 to 12 inches in western Kansas and eastern Colorado. The dwarfing of *Festuca octoflora* and *Lappula occidentalis* often to 2 inches or less in the buffalo-grama sod at Burlington is in marked contrast to their better development under more favorable growth conditions.

The height-growth of the native plant-cover becomes less, in general, from Peru and Lincoln westward. This is due in a large measure to the lesser abundance or complete disappearance of many of the tall-grass dominants in the mixed-prairie association and a greater abundance of buffalo-grass, grama-grass, and certain carices, but also to the poorer development of many species in the drier habitats. Such diminution in height-growth has been noted repeatedly, while actual measurements of a large number of species, including *Agropyrum glaucum,* which ranges throughout the area, shows the validity of this statement. A study of the growth of seedlings and transplants at the several stations (Clements and Weaver, 1921) affords conclusive proof. Similar results were obtained during 1919, when rye, oats, and wheat were measured at 14 different stations. Using the height-growth in the true prairie as unity, the ratios for mixed-prairie and short-grass plains were as follows: rye 100 : 66 : 56, oats 100 : 94 : 85, and winter wheat 100 : 85 : 64. Less favorable growth conditions westward are further indicated both by the smaller number and poorer development of societies of subdominants in the grassland (*cf.* Clements, 1920).

The actual plant production of the native vegetation also correlates directly with that of cultivated crops. During 1920, 30 square-meter quadrats were cut in the undisturbed grassland at each of the several stations. When

air-dried the vegetation yielded an average of 196 grams per square meter at Burlington, 306 at Phillipsburg, and 444 at Lincoln. Wheat-grass, during 1921, gave an average yield per square meter of 400, 457, and 606 grams respectively. These data are typical of those obtained during a series of years (Weaver, 1921).

Similar relations hold as regards the extent of the roots of native vegetation. The roots of seedling grasses and certain subdominant herbs penetrate the

idly and to a greater depth than at Lincoln,
ɜst root-growth was recorded. Similarly,
were found to penetrate from 2 to 4 feet
or Phillipsburg. Regarding the normal
several plant associations, the following
the grassland formation" are instructive.
s of eastern Nebraska, 14 per cent had roots
ɜ first 2 feet of soil; 21 per cent were rooted
ɔw 5 feet; while 65 per cent penetrated to
ıetimes to 12 or even 20 feet.
nixed prairie (hard lands), 11 per cent were
ent were of intermediate depth (2 to 5 feet),
extended well below the fifth foot of soil,
ɜet. Of these, 71 per cent are well adapted
rface soil only is moist.
ːies of the short-grass plains, all but one are
he surface soil. Three are shallow rooted,
nd their roots beyond a depth of 5 feet.
lepth as one goes eastward from the short-
the deep subsoil is constantly moist is in
nade on the root depth of cereals at 14
ıt extent in the true prairie as unity, the
short-grass plains was as follows: Working
100 : 95 : 79; winter wheat, 100 : 93 : 61.
ɔ0 : 65; oats, 100 : 94 : 77; winter wheat

rect correlation may be seen between the
; of crops and that of the native vegetation
onment.

The differences found in the lesser height-growth, smaller yield, and less extensive underground parts, going from the more mesophytic eastern stations to those of greater aridity westward, correlate directly in nearly every way with the growth of native vegetation, whether trees, weeds, or species of the native grass land are considered. The native vegetation growing through a long period of years integrates the climatic conditions during its growth. Thus it is not only an expression of the present conditions, as is true largely of rapidly maturing crops, but is to a large extent a record of conditions that have obtained during a period of many years.

The favorable climate for tree-growth at Peru is indicated not only by the large number of species present, but also by their development both in diameter and height. At Lincoln, forests are confined to the flood-plains. The species are much fewer in number and the trees are smaller both in diameter and height (*cf.* Pool, Weaver, and Jean, 1918). Only a very few species occur along the streams at Phillipsburg, and these are noticeably smaller in every way than those at Lincoln, while the few drought-enduring species which can grow only under cultivation on the plains at Burlington are even smaller of stature.

The variety and abundance of the weed flora of eastern Nebraska, as well as the rank growth of the plants, stand in striking contrast to the paucity of species, their lesser abundance, and poorer development at the western stations. Very marked differences occur even between Phillipsburg and Burlington, low water-content of soil, except in early spring, almost constantly inhibiting normal growth at the latter station. Such widely distributed species as *Grindelia squarrosa* and *Amaranthus retroflexus* reach heights of 3 or more feet in eastern Nebraska, but are often limited to a growth of 6 to 12 inches in western Kansas and eastern Colorado. The dwarfing of *Festuca octoflora* and *Lappula occidentalis* often to 2 inches or less in the buffalo-grama sod at Burlington is in marked contrast to their better development under more favorable growth conditions.

The height-growth of the native plant-cover becomes less, in general, from Peru and Lincoln westward. This is due in a large measure to the lesser abundance or complete disappearance of many of the tall-grass dominants in the mixed-prairie association and a greater abundance of buffalo-grass, grama-grass, and certain carices, but also to the poorer development of many species in the drier habitats. Such diminution in height-growth has been noted repeatedly, while actual measurements of a large number of species, including *Agropyrum glaucum*, which ranges throughout the area, shows the validity of this statement. A study of the growth of seedlings and transplants at the several stations (Clements and Weaver, 1921) affords conclusive proof. Similar results were obtained during 1919, when rye, oats, and wheat were measured at 14 different stations. Using the height-growth in the true prairie as unity, the ratios for mixed-prairie and short-grass plains were as follows: rye 100 : 66 : 56, oats 100 : 94 : 85, and winter wheat 100 : 85 : 64. Less favorable growth conditions westward are further indicated both by the smaller number and poorer development of societies of subdominants in the grassland (*cf.* Clements, 1920).

The actual plant production of the native vegetation also correlates directly with that of cultivated crops. During 1920, 30 square-meter quadrats were cut in the undisturbed grassland at each of the several stations. When

air-dried the vegetation yielded an average of 196 grams per square meter at Burlington, 306 at Phillipsburg, and 444 at Lincoln. Wheat-grass, during 1921, gave an average yield per square meter of 400, 457, and 606 grams respectively. These data are typical of those obtained during a series of years (Weaver, 1921).

Similar relations hold as regards the extent of the roots of native vegetation. The roots of seedling grasses and certain subdominant herbs penetrate the mellow loess soil at Peru more rapidly and to a greater depth than at Lincoln, while at Burlington the shallowest root-growth was recorded. Similarly, numerous mature prairie plants were found to penetrate from 2 to 4 feet deeper at Peru than at Lincoln or Phillipsburg. Regarding the normal depth of root penetration in the several plant associations, the following data from "Root development in the grassland formation" are instructive. Of 43 species studied in the prairies of eastern Nebraska, 14 per cent had roots which seldom extended beyond the first 2 feet of soil; 21 per cent were rooted well below 2 feet but seldom below 5 feet; while 65 per cent penetrated to depths greater than 5 feet and sometimes to 12 or even 20 feet.

Among 36 species excavated in mixed prairie (hard lands), 11 per cent were rather superficially rooted, 45 per cent were of intermediate depth (2 to 5 feet), and 44 per cent had roots which extended well below the fifth foot of soil, many in fact to a depth of 7 to 9 feet. Of these, 71 per cent are well adapted to absorb water even when the surface soil only is moist.

Of 8 of the most important species of the short-grass plains, all but one are adapted for water absorption in the surface soil. Three are shallow rooted, and only one or two normally extend their roots beyond a depth of 5 feet.

This increasingly greater root depth as one goes eastward from the short-grass plains into regions where the deep subsoil is constantly moist is in agreement with determinations made on the root depth of cereals at 14 stations during 1919. Using root extent in the true prairie as unity, the relative depth in mixed-prairie and short-grass plains was as follows: Working depth of rye, 100 : 92 : 69; oats, 100 : 95 : 79; winter wheat, 100 : 93 : 61. Maximum depth of rye, 100 : 90 : 65; oats, 100 : 94 : 77; winter wheat 100 : 80 : 51.

From the foregoing data a direct correlation may be seen between the development of the tops and roots of crops and that of the native vegetation growing in the same general environment.

VI. DEPTHS AT WHICH PLANTS ABSORB WATER AND NUTRIENTS.

Repeated examination of developing root systems of plants during the past six years (Weaver, 1915, 1917, 1919, 1920), together with the usual findings of great depth of penetration where growth conditions were favorable, have led the writers to gravely doubt the accuracy of statements current in the literature on soils regarding the depth at which plants absorb. The common viewpoint is well stated as follows in one of our best modern works (Russell, 1917 : 56).

"It is well known that only the top 6 or 8 inches of the soil is suited to plant life, and that the lower part, or subsoil, plays only an indirect part in plant nutrition. We shall, therefore, confine our attention almost exclusively to the surface layer."

It seems certain that in many of our native grassland species which possess strong tap-roots with little or no branching in the surface foot or two of soil, little if any absorption occurs in these soil layers, because of the cutinized or suberized root cortex. *Rosa arkansana, Kuhnia glutinosa, Liatris punctata,* and *Amorpha canescens* are common examples. Among cultivated crops, life-history studies indicate that older alfalfa and sweet-clover plants, for example, are very similar to the preceding in this regard. Even among fibrous-rooted species, including cereals, it must be kept distinctly in mind that the number of roots in any given area of soil is no criterion of their activity. It seems probable that with increasing age the older roots are cutinized or suberized, and unless new branches are put out, the seat of maximum absorbing activity is transferred to soil layers of ever-increasing depth, inhabited by the younger parts of the root system. While it is clear that many new roots develop in the surface soils, especially from plants that tiller, and that older ones normally develop abundant laterals, yet it seems equally certain that the bulk of the surface roots are developed earlier in the life of the plant and because of age and consequent structural changes must be less active absorbers at a time when rapid development of a network of new roots is occurring at greater depths. A casual perusal of the preceding pages should impress the reader with the great depth to which certain crops penetrate and with the abundance of roots below the level of cultivation (6 to 8 inches). Extended examinations of the root distribution of winter wheat and rye at 10 different stations in true-prairie and mixed-prairie areas of Nebraska, Kansas, and South Dakota show conclusively their deep-rooting habits. The average maximum depth attained by these cereals was 5.0 and 5.1 feet respectively, while the average working depth (the soil-level to which the bulk of the roots penetrate and consequently where they are very abundant) was 3.7 feet for wheat and 3.9 feet for rye. Other crops, such as red clover and alfalfa, were found to be rooted very much deeper (Weaver, 1920). In fact, in nearly all cases where the roots of crop plants were excavated, the total development below the cultivated soil-layer was as great and usually much greater than that in the surface soil. Among native plants, the bulk of the root system in the great majority of cases lies below the surface foot, and the same holds true for many crop plants, including especially the fall-planted cereals. The dependence of plants upon the deeper-seated portion of their root systems is

well illustrated in times of drought, where the vegetation remains unwilted and crops do fairly well even after the water in the surface 6 inches of soil has been nearly or entirely exhausted.

Preliminary Experiments.

During 1919, preliminary experiments were conducted in the greenhouse at the University of Nebraska. White Kherson oats was grown in containers 1.5 feet in diameter and 2.5 feet deep. These were filled with a fertile loam soil at an optimum and uniform water-content. The experiment extended from February 4 to April 1. The soil, both in the containers with plants and those without plants (used for checks), was sampled for water-content at intervals of 14 days. During the period of March 4 to 18, when the plants were 28 to 42 days old, a marked loss of water (3.5 to 8.3 per cent) was determined at depths of 1 to 2.5 feet in the containers with plants, while the controls lost only 1.3 per cent at the 1.5-foot level and none at greater depths. Similar results were obtained for the following two weeks' interval, at the end of which (April 1) the plants, then 12 inches tall, were unearthed. Root distribution in the deeper soils corresponded with the amounts of water removed at the various levels.

Such experiments, while indicative, are subject to two fundamental criticisms. Drought in the surface soil might result in a deeper penetration of roots, while water from lower levels might move to higher ones which have been more or less depleted of their supply, either from evaporation or from absorption by the plants. Thus less absorption might take place at deeper levels than the water-content samples would indicate. Moreover, in its upward or downward movement, nutrients might be carried from one level to another by the water. Although the capillary movement of water in soils has been shown by Alway (1913, 1917), Burr (1910), and others to be much less than formerly supposed, experiments were devised to check out all movements of either water or nutrients from one soil-layer into another, except through the roots. In filling the containers, the soil, after being brought to the desired water-content, was firmly compacted and then sealed with a layer of wax. This consisted of 85 per cent paraffin or parowax and 15 per cent petrolatum (Briggs and Shantz, 1912). The seal was applied hot, so that it penetrated a little into the soil, and when it cooled clung tenaciously to the soil particles. It varied from 2 to 3 mm. in thickness. When it had cooled and hardened, another layer of soil, usually 6 to 12 inches thick, was added, and the process repeated until the container was filled. Oats, barley, and other plants were grown in containers where the soil was thus separated into hermetically sealed layers of varying thickness. The roots of plants grown in these soils were distributed evenly throughout the soil-mass, penetrating the wax layers without difficulty. In fact, no external differences could be noted between roots growing through the seal and those in ordinary soil (plates 9 B and 9 C).

This method furnishes at once a means of determining the amount of water or nutrients removed at any given level to which the roots penetrate. Moreover, by using a series of containers in which plants of the same age are grown, it is possible by opening containers from time to time to determine the absorbing activity of the roots at the various levels at any stage in the development of the crop.

Field Experiments, 1920.

During the spring and summer of 1920, experiments were conducted to determine more precisely the water-absorbing power of crop-plants at various soil-levels. Barley was employed and the crop was grown under field conditions adjoining the crop-plats already described on the lowland area at Belmont.

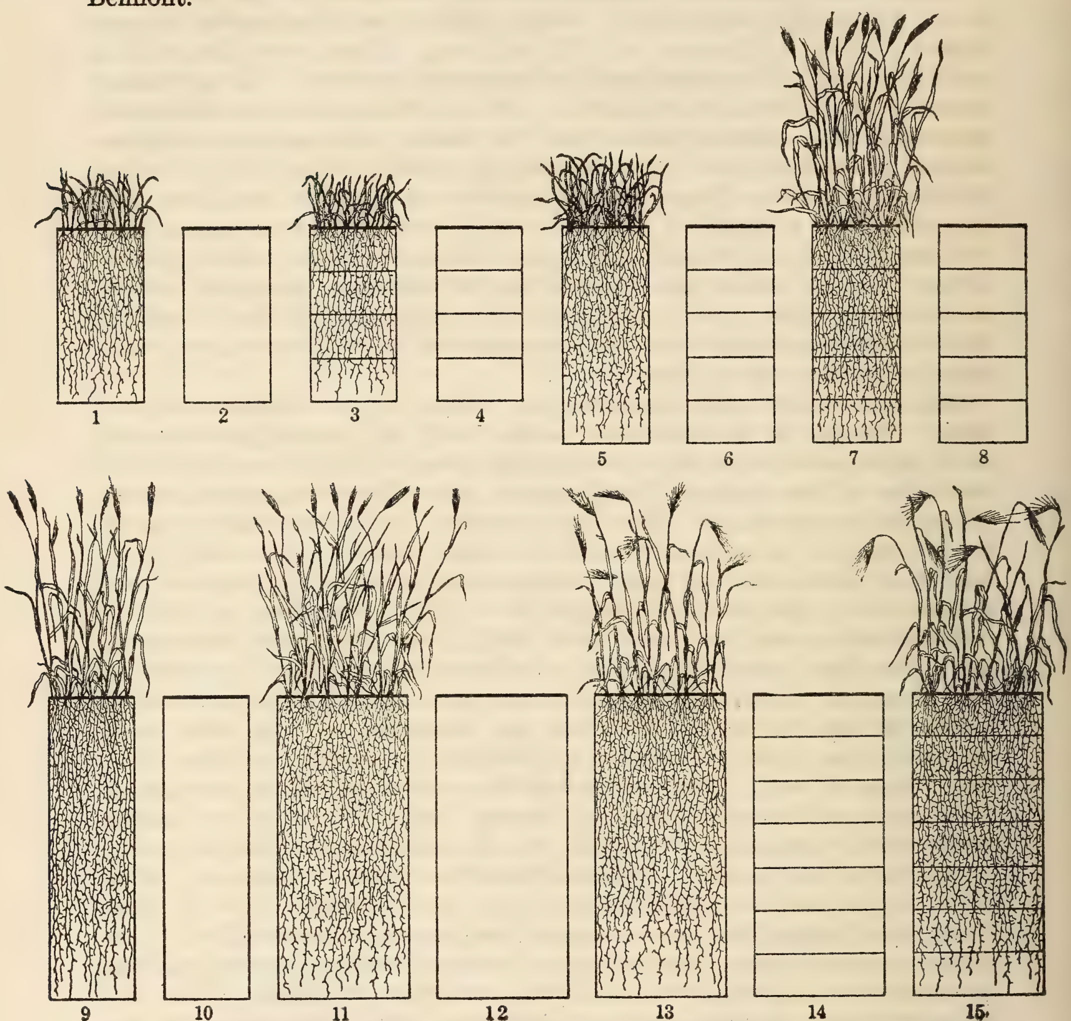


Fig. 40.—Diagram of containers and development of barley, 1920. Positions of wax seals, 6 inches apart, indicated by cross-lines.

Containers of large size and especially designed for ease of root examinations were used. The larger ones, in which the crops were grown for long periods or to maturity, were cylindrical in shape, 1.5 feet in diameter, and 3.5 feet deep. They consisted of heavy galvanized sheet-iron rolled into a cylinder, with an overlap on the edge of 5 inches, fitted into a one-piece circular bottom with an upright edge of 0.5 inch, and held in place by three

metal hoops fastened with small bolts. When filled with firmly compacted soil, the smooth overlapping edges fit tightly, while at the end of the experiment the whole core of soil could easily be exposed for examination by simply removing the bottom of the containers and the hoops (plate 9, A and B). Plants grown for shorter periods were in containers of the same design, but with a diameter of 1 foot and a depth of either 2 or 2.5 feet. In this experiment 16 containers were used, but the plants in one were accidentally destroyed.

On May 19 to 21 two long trenches were dug to a depth of 2 to 3.5 feet, the rich, alluvial, silt-loam soil being kept separate from the somewhat more clayey subsoil. The containers were then placed in a row in the trenches about 6 inches apart, the lower end of each container resting evenly upon its inverted bottom. The soil which had been removed from the trench was next mixed very thoroughly by shoveling it back and forth on an improvised platform. It was in excellent tilth, with a water-content of about 30 per cent. The subsoil, similarly treated on a separate platform, had approximately the same water-content. After mixing, the subsoil and surface soil were slowly poured into the containers and continuously tamped, so that they were compacted to a degree not unlike that of the natural soil in the adjoining plats, where roots were repeatedly excavated. When filled, the soil in each container was again at approximately the same level it had formerly occupied. In filling the containers, duplicate samples were taken at the several levels (mostly at 6-inch intervals) for water-content. Moreover, at the time of filling, wax seals were inserted in about one-half of the containers between the several layers of soil at intervals of 0.5 foot, beginning at 6 inches depth. Finally, each container was fitted with a sloping wooden roof, the soil having been mounded up so as to fit snugly under the roof. Thus no rain could enter except through a central slit three-fourths inch wide and with a length equal to the diameter of the container, 1 or 1.5 feet respectively. Through this opening barley was planted thickly at a depth of 1.5 inches on May 19, but in only the odd-numbered containers, the ones with even numbers being used as checks. The trench about the containers was refilled, the soil thoroughly compacted and ridged up in such a manner that drainage was away from the disturbed area, the surface-water being carried away through shallow ditches about 2 feet distant on either side of the original trench. Grass was allowed to grow on this disturbed area which adjoined the crop plats. At four periods during June and July, when the crop was in various stages of development, certain containers were removed, and the root distribution and the water-content determined. The size and arrangement of containers and the position of the seals, as well as the relative heights and root development of the several plant-groups at the time of examination, are shown in figure 40.

On May 25 to 27, when the barley was about an inch high, the plants were thinned to 20 and 25 in each of the small and large containers respectively. By June 4 they had reached a height of 4 inches and practically all had 3 or 4 leaves. The much more rapid development of this late-planted crop than that sowed April 9 (p. 41) is clearly correlated with environmental conditions which have already been discussed (*cf.* p. 44 and fig. 20). On June 15 the plants were 6 to 8 inches high; some had 2 or 3 tillers. At this time they were

again thinned and containers 1, 2, 3, and 4 were removed from the trench and examined, while soil samples were obtained, by the use of a geotome, from containers 5, 9, 10, and 11. After securing the samples the holes left by the soil-tube were carefully refilled with moist soil, which was tamped into place.

TABLE 30.—*Water-content of soil on May 19 and June 15.*

Container.	Depth of sample.	May 19.	June 15.	Loss.
	feet.	*p. ct.*	*p. ct.*	*p. ct.*
No. 1.....	0 to 0.7	30.8	22.5	8.3
	0.7 to 1.3	28.8	26.5	2.3
	1.3 to 2	26.9	25.2	1.7
No. 3.....	0 to 0.5	27.7	23.5	4.2
	0.5 to 1	28.3	26.1	2.2
	1 to 1.5	27.9	27.1	0.8
	1.5 to 2	25.9	26.1	+0.2
No. 5.....	0 to 0.7	29.3	18.8	10.5
	0.7 to 1.3	31.5	26.5	5.0
	1.3 to 2	31.2	28.0	3.2
No. 9.....	0 to 0.5	30.4	24.6	5.8
	0.5 to 1	28.6	24.9	3.7
	1 to 1.5	28.5	25.9	2.6
	1.5 to 2	29.8	27.8	2.0
	2 to 2.5	29.8	29.0	0.8
	2.5 to 3	28.4	29.3	+0.9
	3 to 3.5	27.2	27.8	+0.6
No. 11....	0 to 0.5	32.5	24.4	8.1
	0.5 to 1	31.8	23.7	8.1
	1 to 1.5	30.4	23.0	7.4
	1.5 to 2	30.6	28.6	2.0
	2 to 2.5	27.7	28.3	+0.6
	2.5 to 3	27.7	27.3	0.4
	3 to 3.5	27.6	27.3	0.3
No. 2.....	0 to 0.7	29.5	31.1	+1.6
	0.7 to 1.3	29.6	30.6	+1.0
	1.3 to 2	31.9	32.4	+0.5
No. 4.....	0 to 0.5	27.1	28.2	+1.1
	0.5 to 1.0	28.0	28.6	+0.6
	1.0 to 1.5	28.6	28.3	0.3
	1.5 to 2	28.6	29.0	+0.4
No. 10....	0 to 0.5	27.2	27.8	+0.6
	0.5 to 1	27.0	27.6	+0.6
	1 to 1.5	28.3	28.0	0.3
	1.5 to 2	28.1	27.8	0.3
	2 to 2.5	27.4	27.8	+0.4
	2.5 to 3	30.5	30.3	0.2
	3 to 3.5	30.2	30.1	0.1

The water-content at the various levels, together with the loss during the period, may be seen in table 30. These data, with a statement of root distribution, are summarized in table 31, while the actual root distribution is shown diagrammatically in figure 40.

An examination of table 30, and especially table 31, shows that the water-content in the several containers with plants had been reduced from 4 to 10

per cent in the surface 6 or 8 inches, from 2 to 8 per cent in the second 6 or 8 inches, from 1 to 7 per cent in the third 6 or 8 inches, and from 0 to 2 per cent in the next 6-inch layer. Below 2 feet depth no change in water-content had occurred that could not be easily accounted for by variations in soil sampling. These losses are clearly correlated with root distribution, for although the plants were only 27 days old, the roots were very abundant not only in the surface, but also at depths of 8 to 16 inches, while some penetrated to 2 feet. This root development is altogether in agreement with that of barley grown in field plats. Moreover, the root distribution in the container with the wax seals was identical, so far as could be determined, with that in the unsealed soil. Even the most delicate root-ends showed no external differences where they encountered the wax seal.

TABLE 31.—*Water lost during the period May 19 to June 15.*

Container.	Percentage of water removed at various depths, in feet.							Remarks.
	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	2.5 to 3	3 to 3.5	
No. 1..	[1]8.3	[2]2.3	[3]1.7	....	....	....	....	14 plants; some roots penetrated 2 feet but were not abundant below 1.5 feet; soil to 16 in. well filled with roots.
No. 3..	4.2	2.2	0.8	+0.2	....	....	....	10 plants; root distribution approximately as in No. 1, but fewer.
No. 5..[4]	[1]10.5	[2]5.0	[3]3.2	....	....	....	....	20 plants.
No. 9..[4]	5.8	3.7	2.6	2.0	0.8	+0.9	+0.6	About 15 plants.
No. 11.[4]	8.1	8.1	7.4	2.0	+0.6	0.4	0.3	About 20 plants.
No. 2..	[1]+1.6	[2]+1.0	[3]+0.5	....	....	....	....	No plants.
No. 4..	+1.1	+0.6	0.3	+0.4	....	....	....	No plants.
No. 10..	+0.6	+0.6	0.3	0.3	+0.4	0.2	0.1	No plants.

[1] Samples taken at depth of 0 to 0.7 foot.
[2] Samples taken at depth of 0.7 to 1.3 foot.
[3] Samples taken at depth of 1.3 to 2 feet.
[4] Soil-tube holes refilled, plants undisturbed.

TABLE 32.—*Water-content of soil at the several intervals.*

Container No.	Depth of sample.	Loss, May 19 to June 15.	Water-content.		Loss, June 15 to 28.
			June 15.	June 28.	
	feet.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
5.......	0 to 0.7	10.5	18.8	14.5	4.3
	0.7 to 1.3	5.0	26.5	16.4	10.1
	1.3 to 2	3.2	28.0	13.0	15.0
6.......	0 to 0.5	...	[1]25.1	24.8	0.3
	0.5 to 1	...	27.8	26.9	0.9
	1 to 1.5	...	28.0	27.2	0.8
	1.5 to 2	...	26.5	26.3	0.2
	2 to 2.5	...	26.0	26.8	+0.8

[1] Water-content at all levels in this container is for May 19.

On June 28, when the plants had an average height of about 10 inches, containers 5 and 6 were removed (fig. 40). A glance at table 32 shows that the seals in the check container were preventing appreciable water-loss, while any intake in the surface 6 inches had apparently been balanced by evaporation. During the interval of 13 days since the last examination of container 5, 4 per cent of water had been lost from the surface 8 inches, but this was less than half the absorption from the 8 to 16 inch level, while 15 per cent had been absorbed from the 1.3 to 2 foot depth. Clearly, the roots at this stage of development were more active in the deeper soil. Unfortunately the 2 to 2.5 foot samples were lost in drying. The roots of the 20 plants in this container extended to the 2.5 foot-level and were very abundant at a depth of 2 feet. These data indicate that the surface roots were much less actively absorbing than the deeper, younger portions. The loss in the top 8-inch layer may be accounted for in part by new roots from the tillers, as well as from the parent plant. Considerable water was still available at all depths, since the hygroscopic coefficient is rather uniformly about 10 per cent (*cf.* table 10).

On July 16, containers 9, 10, and 11 were excavated, opened, and examined. The plants were about 2.3 feet tall, had tillered extensively, and were in the early milk stage. The roots were uniformly distributed throughout the soil, except that they were less abundant at depths of 2.8 to 3.5 feet, i. e., below the working level (fig. 40). An examination of table 33 (sixth column) shows

TABLE 33.—*Water-content of soil at several intervals to July 16.*

Container.	Depth of sample.	Loss May 19 to June 15.	Water-content June 15.	Water-content July 16.	Loss June 15 to July 16.	Loss May 19 to July 16.
	feet.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
No. 9[1]	0 to 0.5	5.8	24.6	18.6	6.0	11.8
	0.5 to 1	3.7	24.9	18.9	6.0	9.7
	1 to 1.5	2.6	25.9	16.4	9.5	12.1
	1.5 to 2	2.0	27.8	16.3	11.5	13.5
	2 to 2.5	0.8	29.0	18.7	10.3	11.1
	2.5 to 3	+0.9	29.3	17.9	11.4	10.5
	3 to 3.5	+0.6	27.8	25.7	2.1	1.5
No. 11[2]	0 to 0.5	8.1	24.4	16.8	7.6	15.7
	0.5 to 1	8.1	23.7	15.7	8.0	16.1
	1 to 1.5	7.4	23.0	16.8	6.2	13.6
	1.5 to 2	2.0	28.6	16.7	11.9	13.9
	2 to 2.5	+0.6	28.3	16.8	11.5	10.9
	2.5 to 3	0.4	27.3	21.4	5.9	6.3
	3 to 3.5	0.3	27.3	25.5	1.8	2.1
No. 10[3]	0 to 0.5	+0.6	27.8	29.3	+1.5	+2.1
	0.5 to 1	+0.6	27.6	27.9	+0.3	+0.9
	1 to 1.5	0.3	28.0	27.8	0.2	0.5
	1.5 to 2	0.3	27.8	27.2	0.6	0.9
	2 to 2.5	+0.4	27.8	28.4	+0.6	+1.0
	2.5 to 3	0.2	30.3	29.3	1.0	1.2
	3 to 3.5	0.1	30.1	28.9	1.2	1.3

[1] Eleven plants, mostly with 3 to 7 tillers; 2.3 feet tall and in the milk stage.

[2] Twelve plants, mostly with 3 to 5 tillers each, some with 7; about 2.3 feet tall and in milk stage. Roots uniformly distributed, except not so abundant in last 6 to 9 inches.

[3] No plants.

little change in water-content of the check container (No. 10) during the interval from June 15 to July 16, but a marked loss from the ones with crops, especially at depths of 2 to 3 feet. Thus, the activity shown by the deeper portions of the roots on June 28 is here confirmed. Indeed, the total water absorbed at the several levels (May 19 to July 16) is about the same in amount to a depth of 3 feet (table 33, last column). Further evidence for this conclusion is given in table 34, which shows the water-loss from the sealed containers 7 and 8 during this interval.

TABLE 34.—*Water-content of sealed containers, May 19 and July 16.*

Container No. 7, eight plants, roots quite uniformly distributed throughout the container.				Container No. 8, no plants.		
Depth of sample.	May 19.	July 16.	Loss.	May 19.	July 16.	Loss.
feet.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
0 to 0.5	25.6	15.9	9.7	26.0	28.3	+2.3
0.5 to 1	25.7	14.3	11.4	28.1	27.9	0.2
1 to 1.5	26.3	16.4	9.9	29.5	30.0	+0.5
1.5 to 2	26.9	20.7	6.2	29.0	30.4	+1.4
2 to 2.5	28.3	22.8	5.5	28.2	28.7	+0.5

On July 29 the barley was nearly ripe. The plants in the remaining containers were 2.2 feet tall and were rather badly rusted with *Puccinia graminis tritici*. The roots in both the sealed and unsealed soil were rather uniformly distributed to near the bottom of the containers, a depth of 3.5 feet. Only in the deepest soil were they less numerous. The plants had tillered extensively and the dense mat of roots was most pronounced to a depth of 2 feet. None of the 4 containers had been disturbed in any way since May 21, except that on June 28 a liter of water was slowly added to each through the slit in the roof

TABLE 35.—*Total water lost at the several levels from May 21 to July 29.*

Depth of sample.	Container No. 12.[1]			Container No. 14.[1]			Container No. 13.[2]			Container No. 15.[3]		
	May 21.	July 29.	Loss.	May 21.	July 29.	Loss.	May 21.	July 29.	Loss.	May 21.	July 29.	Loss.
feet.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
0 to 0.5	30.9	28.3	2.6	32.6	30.2	2.4	32.5	13.5	19.0	33.3	13.1	20.2
0.5 to 1	32.0	30.4	1.6	33.3	33.0	0.3	34.5	16.7	17.8	33.3	14.5	18.8
1 to 1.5	31.8	30.7	1.1	33.0	33.6	+0.6	32.7	16.3	16.4	31.5	15.8	15.7
1.5 to 2	30.4	30.6	+0.2	32.0	32.9	+0.9	34.0	17 4	16.6	32.5	16.9	15.6
2 to 2.5	30.4	30.3	0.1	31.7	32.5	+0.8	33.7	20.5	13.2	31.9	17.9	14.0
2.5 to 3	31.3	31.3	0.0	32.9	31.9	1.0	32.6	23.5	9.1	31.5	19.5	12.0
3 to 3.5	30.6	31.8	+1.2	30.6	30.3	0.3	30.8	23.9	6.9	34.6	23.3	11.3

[1] No plants.
[2] Eight plants, average height 2.2 feet; 2 to 6 tillers each; roots normally distributed to bottom of container.
[3] Fifteen plants, average height 2.2 feet; 2 to 8 tillers each; roots normally distributed to bottom of container.

of the container. The total water lost at the several depths, both by the sealed and unsealed checks and by the cropped containers, is shown in table 35. Allowing for losses from the surface layer by direct evaporation (as indicated by the checks), the water removed by absorption is quite uniform in amount (about 16 to 18 per cent) to a depth of 2 feet. Below this level it gradually diminished in amount to the maximum depth, but even below 3 feet a large amount of water was removed. The movement of water by capillarity plays a rather unimportant rôle in replenishing water at the various levels from those adjacent, as may be inferred from the water relations of unsealed containers when compared with those where such movement was prevented by the wax seal.

Greenhouse Experiments, 1920–21.

During the fall of 1920 another series of experiments was started in the greenhouse at the University of Nebraska, with the object of determining the depth at which crop plants remove nutrients from the soil. On October 16, 44 bags of soil, each weighing about 125 pounds, were secured from the upland experimental plats about 3 miles north of Lincoln (p. 40). The mechanical and chemical analyses of this soil to the depth to which it was removed (4 feet) are given in tables 8 and 9. In securing the samples, two large rectangular trenches were dug and the soil removed from the first, second, third, and fourth foot and bagged separately.

Twelve large containers were employed for growing the crop. These were the same as those used in the field experiment, except that the smaller ones were enlarged so that all had a depth of 3.5 feet. Five had a diameter of 1.5 feet, while the others were only 1 foot wide. Before filling the containers the soil from each level was spread out on the cement floor of the greenhouse and worked over until all lumps were broken up and the soil thoroughly mixed. Water was slowly added as the mixing proceeded until the water-content was at an optimum, and, after standing for a period, uniformly distributed throughout the soil mass.

The nutrients used in this set of experiments were limited to nitrates for several reasons. Nitrates, unlike phosphates and potash, are not adsorbed by soil and can be completely recovered by simply leaching with water. Consequently a known quantity could be added to the soil when the containers were filled, and its use by the plant determined by a chemical analysis of the soil after the containers were opened. Not being adsorbed, they can be expected to diffuse readily throughout the soil along with the movement of water. They are used in comparatively large quantities by such crops as barley, which was employed in this experiment, and hence the error in determining by analysis the percentage used by the plant is reduced to a minimum. Furthermore, the presence or absence of an abundance of nitrates is shown by the foliage of the plant in a striking manner.

The soil was impregnated with sodium nitrate at the rate of 400 parts per million (i. e., 292 parts per million of NO_3) before it was placed in the containers. This was accomplished by weighing the amount of thoroughly pulverized and well-watered soil necessary to fill a container to a depth of 1 foot when compacted and adding to this the proper amount of salt in a dry state. The soil was again thoroughly mixed after the salt was added.

Thus the total nitrate-content at the beginning of the experiment was that of the impregnation plus that already in the soil as it came from the field. After the water-content of the soil had been determined, the amount of NO_3 used in fertilizing was calculated to the dry basis for each respective level and these figures were used in the tabulations.

The containers were placed a few inches apart on the cement floor, and after soil from the fourth foot was tamped into the bottom 8 inches of each, the usual wax seal was applied. The soil from the third, second, and surface foot was then placed in its relative position in each container in a similar manner, the several layers being separated by wax seals. The containers were filled in pairs, any two in a pair being exactly alike regarding the position of the impregnated soil, etc., except that one was provided with apparatus for aerating the soil at the four separate levels. This consisted of eight thick-walled glass tubes about a centimeter in diameter also placed in pairs, one on each side of the container, and of such length that they extended from the surface where they were kept corked, well into the first, second, third, or fourth foot of soil respectively. Thus by removing the corks and attaching a large exhaust pump to one tube of the pair, moist air could readily be drawn through the hermetically sealed layer of soil. All the even-numbered containers were thus provided for aeration.

The soil in containers 1 and 2 was impregnated with nitrates in the first foot only; in 3 and 4 in the second foot; in 5 and 6 in the third foot; in 7 and 8 in the fourth foot; that in 9 and 10 was furnished with the salt at all levels, while none was added to the soil in containers 11 and 12.

Before adding the surface seal, two thin strips of wood, about 1.5 inches in width, were placed edgewise across the containers and partially sunken in the soil in such a manner that the seal was prevented from covering an area of soil about 1.5 inches wide extending across the container. In this soil Manchuria barley was planted thickly on November 4, after which it was covered to a depth of about an inch with dry sand to retard water-loss from the unsealed surface. The wax seal was then covered with 2 inches of sand and the whole top of each container covered with white oilcloth provided with an opening 1.5 inches in diameter to permit the exit of the plants. The covering was added to exclude any water which might leak through the greenhouse roof during storms or condense on the inner side and drip down. Finally, an inclosure nearly 4 feet high was built around the containers and the whole filled with sand. This insured a more uniform soil-temperature about the developing roots, while barley grown in the sand about the containers, as well as on the adjoining benches, helped to keep atmospheric conditions more nearly comparable with those in the field. The general arrangement of the containers, etc., as well as the development of the crop on December 23, is shown in plate 9 D.

The seed germinated well and the crop was so thick and developed so rapidly that it was necessary to thin it by pulling up some of the seedlings from time to time during the first month after planting. Half of the containers were aerated regularly at intervals of 10 to 14 days until the end of the experiment on March 12, although at no time did the aerated plants as a group show a more marked growth than the unaerated ones. However, the presence of the nitrates had such a pronounced effect upon the growth and color of the

barley that two weeks after germination the plants in containers with sodium nitrate in the first foot of soil were readily designated by a number of uninterested observers. The difference in growth on December 11 in the unfertilized soil of container 12 and that of container 1, where the first foot was enriched with nitrates, is shown in plate 10. At this time a few of the plants had begun to tiller and by December 20 many of the new shoots had three leaves. The plants stood up well, although considerably attenuated because of the low light intensity, while throughout the experiment the more abundant foliage, broader leaves, and darker green color marked the containers with nitrates added in the first and second feet.

On December 21 container No. 5 was taken down and the root system examined. The plants averaged 8.5 inches in height (maximum 14 inches), but the roots were abundant in the first foot of soil only, a few having penetrated a distance of only 4 to 6 inches into the second foot. Thus, during this period of 47 days, the above-ground parts had developed scarcely further than plants grown in the field for only 27 days, while the root extent was not much more than half as great (table 31).

From January 18 to February 22 the crops were watered from time to time through the opening in the oilcloth cover and wax seal. Water was added slowly, so that it penetrated the sand between the wooden strips bordering the wax seal and entered the soil below. In this manner a total of 4 liters was added to each of the larger containers and 3.1 liters to each of the smaller ones.

Late in February, the crop, although very short, began to head, but growth proceeded so slowly that by March 12 only a few heads had appeared and none had blossomed. The development of the crop at this time is summarized in table 36, while plate 11 illustrates the difference in growth in the fertilized and unfertilized soils.

TABLE 36.—*Development of crop, March 12.*

Container.	Height in inches.		Max. No. leaves per stalk.	Width of leaves in mm.		Color.	No. of heads.
	Av.	Max.		Av.	Max.		
No. 1..	14	19	7	13	19	Dark green	1
No. 2..	13	18	8	13	18	Do.	2
No. 3..	12	17	5	11	14	Do.	0
No. 4..	12	14	7	13	19	Do.	5
No. 6..	10	15	6	8	13	Pale green	2
No. 7..	10	15	5	7	12	Do.	2
No. 8..	10	15	5	10	14	Do.	0
No. 9..	13	17	8	10	16	Dark green	0
No. 10.	11	16	8	10	13	Do.	1
No. 11.	10	15	5	9	14	Pale green	1
No. 12.	9	19	6	8	13	Do.	0

Table 36 shows that in general the plants in containers with nitrates added to the first or second foot (viz, Nos. 1, 2, 3, 4, 9, and 10) were taller, had a greater number of leaves per plant, and that the leaves were wider and of a dark-green color. Thus the nitrates stimulated vegetative growth, but did not promote flower production. However, even the best developed plants

had made a very poor growth during the 129-day period (November 4 to March 12) when compared with the usual development under field conditions (*cf.* p. 98). Moreover, when the containers were emptied on March 12, so that they might be available for use in the field, it was found that the roots had made even a poorer development relatively than the tops, since the latter were somewhat attenuated because of unfavorable growth conditions.

While the duration, and especially the intensity, of the light were undoubtedly the chief limiting factors to growth (*cf.* Garner and Allard, 1920), brief mention may be made of the other environmental conditions. Thermograph records show that the air-temperature averaged about 75° F. throughout the period. The temperature was maintained within 5° F. of the average more than two-thirds of the time. During November the extremes varied from 50° to 93° F.; throughout December the range of variation seldom exceeded 15° F., a maximum of 90° F. being reached only during two days; during January, owing to an unusual amount of clear weather, temperatures of 90° to 95° F. were reached on several days, while during February and March the extreme range was from 65° to 100° F. Hygrograph records gave an average relative humidity for the several weeks varying from 45 to 65 per cent. During most of the period the average was 50 per cent. Correlated with the rather uniform temperature, the humidity did not fluctuate widely. The minimum fell to 28 per cent on a few occasions, but usually varied from 33 to 38 per cent, while the maximum humidity of 85 per cent was seldom reached, the usual maxima varying from 60 to 68 per cent. The average daily evaporating power of the air recorded by atmometers placed among the plants was 15.1 c. c. A maximum of 19.5 c. c. was determined during the week of December 20 to 27 and a minimum of 12.7 c. c. on December 6 to 13. A good water-content was present in the containers at all times.

Thermograph records secured at a depth of 8 inches in the sand, just outside the containers, which was kept well watered, gave an average temperature of about 70° F. This fell to 65° during one period of two weeks and reached 75° F. in March. The fluctuation from the mean during any week did not exceed 5° F. Records of soil-temperature were also secured at a depth of 3 feet. Temperature fluctuations here took place very slowly; the total variation during the whole period did not exceed 6° F., a temperature of 73° F. being rather uniformly maintained. Thus the growth conditions as regards soil and air temperature were not greatly unlike those of field conditions in June, but quite unlike those under which the field crop makes its early growth. Soil and air moisture were favorable, but the short days of relatively poor illumination were made still less effective by the glass roof cutting off much of the radiant energy. Normally an ordinary clean, double-strength windowpane cuts off 40 to 50 per cent of the light (as measured by its effect upon solio paper), while dust, moisture, etc., collecting upon the glass reduce this amount still further. Aside from this, during midwinter the direct sunlight was cut off for about an hour each day, owing to the proximity of other buildings. On the other hand, weather records show the period to be one with an unusual amount of clear weather.

On March 12 the containers were opened, the root systems examined, and soil samples for water-content and nitrate determinations were taken to com-

pare with those at the beginning of the experiment. Great care was exercised to secure thoroughly representative composite samples for nitrate analysis. A small amount of toluene was added at once to the sample in the air-tight jars to stop bacterial action.

Nitrates were determined by the reduction method, using Devarda's alloy and the method proposed by Whiting, Schoonover, and Richmond (1920). The results of these analyses, together with the data on root extent and water-loss, are summarized in table 37. Final analyses for nitrates were made only in those fertilized soil layers into which the roots extended.

TABLE 37.—*Loss of water and nitrates[1] from November 4, 1920, to March 12, 1921.*

Container.	Depth.	Water-content.			Nitrates, p. p. m.			Root development.
		Nov. 4.	Mar. 12.	Loss.	Nov. 4.	Mar. 12.	Loss.	
	feet.	*p. ct.*	*p. ct.*	*p. ct.*				
No. 1..	0 to 1	25.8	12.6	13.2	393.3	199.4	193.9	A few roots extended 3 or 4 inches into third foot.
	1 to 2	25.1	21.2	3.9	.....	.....	.....	
	2 to 3	23.6	21.4	2.2	.....	.....	.....	
No. 2..	0 to 1	24.8	15.9	8.9	390.0	165.3	224.7	A few roots extended 1 or 2 inches into third foot.
	1 to 2	26.5	21.9	4.6	.....	.....	.....	
No. 3..	0 to 1	24.5	15.4	9.1	.....	.....	.....	All roots confined to first 2 feet.
	1 to 2	24.4	18.9	5.5	394.2	239.4	154.8	
No. 4..	0 to 1	26.5	16.7	9.8	.....	.....	.....	Roots evenly distributed, in first 2 feet only.
	1 to 2	26.3	22.7	3.6	399.7	139.6	260.1	
No. 5[2].	0 to 1	27.1	20.5	6.6	.....	.....	.....	A few roots penetrated 4 to 6 inches into second foot.
	1 to 2	29.7	27.0	2.7	.....	.....	.....	
No. 6..	0 to 1	25.1	18.7	6.4	.....	.....	.....	Roots evenly distributed in first 2 feet only.
	1 to 2	26.5	23.8	2.7	.....	.....	.....	
No. 7..	0 to 1	25.8	17.6	8.2	.....	.....	.....	Very few roots below 1.8 feet.
	1 to 2	26.9	23.3	3.6	.....	.....	.....	
No. 8..	0 to 1	25.9	19.1	6.8	.....	.....	.....	Very few roots below 1.8 feet.
	1 to 2	27.1	22.1	5.0	.....	.....	.....	
No. 9..	0 to 1	25.6	17.4	8.2	392.3	142.4	249.9	Best root development; evenly distributed in first and second foot and quite abundant to 2.5-foot level.
	1 to 2	25.7	23.2	2.5	397.8	165.2	232.6	
	2 to 3	24.6	22.3	2.3	395.7	39.8	355.9	
No. 10.	0 to 1	27.9	17.9	10.0	399.4	85.4	314.0	Evenly distributed in first 2 feet only.
	1 to 2	25.5	24.2	1.3	397.3	54.1	343.2	
No. 11.	0 to 1	25.8	16.7	9.1	24.2	21.3	2.9	Roots in first 2 feet only.
	1 to 2	32.1	21.7	10.4	26.6	11.4	15.2	
No. 12.	0 to 1	24.0	17.2	6.8	19.8	42.7	+22.9	Roots in first 2 feet only.
	1 to 2	26.5	21.7	4.8	26.4	11.3	15.1	

[1] The nitrate-content is given in parts per million of NO_3. This includes not only the NO_3 of the $NaNO_3$ added, but all NO_3 present in the soil when analyzed at the beginning and end of the experiment respectively.

[2] This container was taken down on December 21.

A study of table 37 shows that the roots developed only poorly; in only 3 of the 12 containers did they reach depths greater than 2 feet. Moreover, they were scarcely more than half as abundant as in the earlier field experiment (p. 94). These findings lead the writers to seriously doubt the value of many greenhouse experiments with crop plants when the results are applied to field conditions. Not infrequently the indoor environment is made still less

favorable for growth by the use of too little soil in small containers. In every case the roots were better branched in the fertilized soil layers, and, correlating with the growth of tops, the best root systems were found in containers 1, 2, 3, 4, 9, and 10. Moreover, in general, greater amounts of water were also used by these more vigorous plants, although the water-loss in any case is relatively small, even when the 3 or 4 liters added to each container is taken into account. The loss of nitrates at all levels is pronounced, the plants in container No. 9, which were among the most vigorous of the lot, extracted rather large amounts from the third foot of soil, thus indicating that the deeper portion of the root system is very active in absorption.

In order to determine the amount of nitrification or denitrification taking place in the soil during the period of the experiment, analyses were made of the soils in the control containers (Nos. 11 and 12) at all levels, both at the beginning and at the end of the experiment. These data are given in table 38.

TABLE 38.—*Changes in nitrate-content in unfertilized soil.*

Depth.	Container No. 11, roots in first 2 feet only.			Container No. 12, roots in first 2 feet only.		
	Nitrates, parts per million.			Nitrates, parts per million.		
	Nov. 4.	March 12.	Loss.	Nov. 4.	March 12.	Loss.
feet.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
0 to 1..	24.2	21.3	2.9	19.8	42.7	+22.9
1 to 2..	26.6	11.4	15.2	26.4	11.3	15.1
2 to 3..	55.0	25.6	29.4	28.6	37.0	+ 8.4
3 to 4..	24.2	65.5	+41.3	28.6	42.7	+14.1

Table 38 shows that the soil at all depths was poor in nitrates when taken from the field. Leguminous crops had not been grown on the area from which the soil was secured for at least three seasons, during which period it had borne Sudan grass and oats. In the unfertilized soil layers where roots occurred changes in the nitrate-content were small when compared with the large amounts removed from the fertilized layers (table 37). In the deeper layers, where no roots occurred the increase or decrease in the nitrate-content is proportionally small. Thus it may be seen that nitrification and denitrification affect the results given in table 37 to no great degree.

FIELD EXPERIMENTS, 1921.

Early in the spring of 1921 an extensive series of experiments on the absorption of nitrates by several crops was begun. In addition to Manchuria barley, Early Ohio potatoes (*Solanum tuberosum*), and Iowa Silver Mine corn (*Zea mays indentata*), three native grasses were employed. These were wheat-grass (*Agropyrum glaucum*), big bluestem (*Andropogon furcatus*), and little bluestem (*A. scoparius*).

Large oak barrels 1.7 feet in minimum diameter and 2.8 feet deep were used in part, especially for the earlier stages of growth, but these were supple-

mented by heavy, water-tight, cylindrical, galvanized-iron containers 2 feet in diameter and 3.5 to 4 feet deep, while the one for corn measured 3 feet in diameter and 5 feet deep. Sufficient soil to fill the containers was secured from both the upland and lowland crop plats north of Lincoln (p. 40) on February 20 and stored in large piles in a dry place until March 30–31, when it was placed in the containers. These soils were chosen because they were from the same plats as those used in the preceding experiments and both their mechanical and chemical composition had been determined (tables 8 and 9). Care was exercised to keep the soils from the several levels to 4 feet separated. When taken from the field they were in such excellent condition regarding water-content that it was unnecessary to add more water when working them over to break up lumps, etc. During storage they were kept well covered to reduce water-loss.

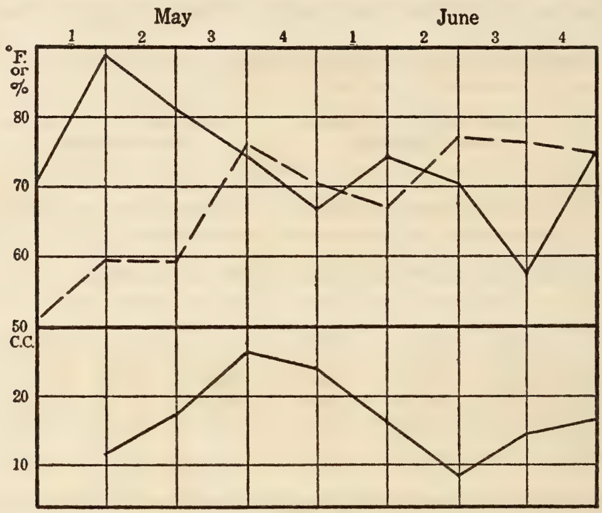


Fig. 41.—Average daily temperature (long broken lines), humidity (upper solid line), and average daily evaporation at Lincoln, 1921.

On March 30–31 a large trench was dug in the field where the 1921 crops were grown (p. 80), and the containers, 16 in number, placed close together in a row in such a manner that the tops were about 4 inches above the surface of the soil. The prepared soil from the deeper levels was then poured slowly into the containers, where it was tamped into place. When filled, the soil in each container (with certain exceptions to be noted) occupied the same relative position as regards depth that it had occupied in the field. Barley was grown in the lowland soil; potatoes in that from the upland.

Sodium nitrate was added at certain sealed levels at the same rate as in the preceding experiment (viz, 400 p. p. m. of $NaNO_3$ based on the wet weight of the soil). In this series, however, the proper amount for the weighed soil at any level was dissolved in about 0.5 liter of water, which was poured upon the soil after it had been placed in the container. This facilitated rapid diffusion, and it seems probable that within a period of 2 weeks the nitrate was rather uniformly distributed throughout the soil-mass. Triplicate samples

for water-content determinations and large composite samples for nitrate determinations were secured at all levels at the time the containers were filled and before the nutrient was added.

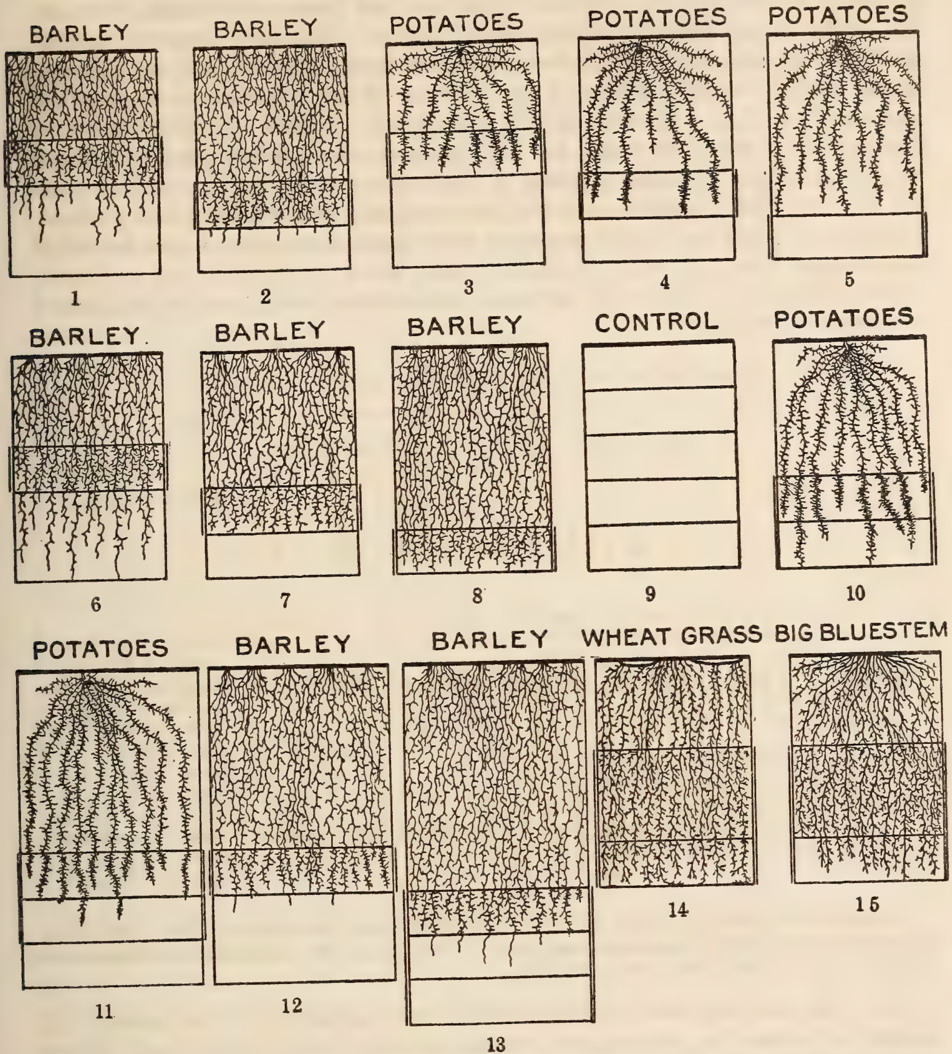


FIG. 42.—Diagram of containers and root development of crops, 1921. Horizontal lines (6 inches apart, except in last two) indicate position of wax seals and double vertical lines position of nutrients.

When the containers were filled within 2 inches of the tops, two thin wooden strips, about 1.5 inches in width and as long as the diameters of the containers, were placed edgewise and partially sunk into the soil so as to prevent the wax seal from covering the area of soil (about 1.5 inches in width) in which the crops were to be planted. Finally, the wax seal was covered with 2 inches of sand. Next a light-green wooden roof, with sufficient slope to cause the water to run off but with an opening 1.5 inches wide and as long as the diameter of the

container, was fastened in place. Before putting the wooden strips in position, however, pieces of oilcloth were inserted under them in such a manner that one end extended an inch or two under the wax seal, while the other lined the inside of the opening between the strips and came up through the roof, upon which it was folded back and tacked down. This gave a smooth surface against which the plants might later be blown back and forth free from injury during windy weather (plate 12 B). In case of the potatoes, a rectangular opening about 3 by 4 inches was left in the roof. Similar modifications from that described were also made for the corn and wild grasses, the latter being planted as sods. A small amount of earth was placed in the opening thus left, the crop planted, and a mulch of about an inch of dry sand added to check water-loss. Both barley and potatoes were planted on April 1, the halves of two potatoes being placed in the soil of each of the several containers at a depth of about 4 inches. The barley, as usual, was planted thickly and later thinned to the desired stand.

TABLE 39.—*Loss of water and nitrates April 1 to May 25.*

Container.	Depth.	Water-content.			Nitrates, parts per million.				Root development.
		Apr. 1.	May 25.	Loss.	Apr. 1.	Gain by nitrification.[1]	May 25.	Loss.	
	feet.	*p. ct.*	*p. ct.*	*p. ct.*					
No. 1.	0 to 0.5	28.5	19.7	8.8	.....	.....	.....	.....	Roots very abundant to 1.5 ft.; also extended throughout the 1.5 to 2 foot layer, but were relatively few.
	0.5 to 1	28.6	22.5	6.1	.....	.....	.....	.....	
	1 to 1.5	25.0	22.3	2.7	376.4	137.5	346.0	167.9	
	1.5 to 2	25.0	24.8	0.2	.....	.....	.....	.....	
	2 to 2.5	23.8	24.7	+0.9	.....	.....	.....	.....	
No. 2.	0 to 0.5	29.9	22.3	7.6	.....	.....	.....	.....	Roots very abundant to 2 ft., beyond which the entirely unbranched tips extended for only 2 or 3 inches.
	0.5 to 1	28.3	20.8	7.5	.....	.....	.....	.....	
	1 to 1.5	25.2	19.9	5.3	.....	.....	.....	.....	
	1.5 to 2	24.2	23.0	1.2	373.2	137.5	365.7	145.0	
	2 to 2.5	24.7	24.5	0.2	.....	.....	.....	.....	

[1] The gain by nitrification has been calculated here, as in the following tables, from data obtained from the control container (see table 41, p. 111), on the assumption that the increase by nitrification varied directly with the time.

After the soil had been replaced about the containers in the trench and ridged up in such a manner as to insure drainage away from them, barley was planted thickly on both sides of the row of containers and in this manner field conditions were approximated (plate 12). During the hotter part of the season the wooden roofs were covered with a mulch of straw to lessen the intensity of the heat. Brome-grass was sowed about the containers in which wild grasses were growing, while the corn was placed in the middle of a small corn-field.

As pointed out on page 88, weather conditions were very favorable for rapid development of the crops, the ripening of the small cereals occurring at least two weeks earlier than normally in eastern Nebraska. The average daily temperature, humidity, and evaporation are shown in figure 41.

On May 25, when the barley had reached an average height of 1.6 feet (maximum height 1.7 feet) and was unfolding the sixth or seventh leaf, containers Nos. 1 and 2 were examined (plate 12 B). The soil in these containers was fertilized at the 1 to 1.5 and 1.5 to 2 feet depths respectively, wax seals being inserted both above and below these levels. The position of these layers, together with the root development, is shown diagramatically in figure 42. It may be noticed that the roots in container 1 are not so abundant below the 1.5-foot level as in container 2. The presence of the fertilized layer in the first container evidently caused this phenomenon, which, in fact, was observed in several other cases. Wherever the roots of any of the crops entered fertilized soil, the degree of branching was very much more pronounced. Table 39 gives a summary of the water and nitrate losses during this 55-day period.

A study of table 39 shows that the roots absorbed almost as much water from the second 6-inch layer of soil as from the first, and also that the water-content below the seal in the 1 to 1.5 foot layer was considerably reduced. The nitrate-content of the soil, as in the following tables, includes not only the NO_3 of the $NaNO_3$ added, but all NO_3 present in the soil when analyzed at the beginning and end of the experiment, respectively. The nitrate-losses at depths of 1 to 1.5 and 1.5 to 2 feet respectively show clearly the root activities at these levels.

On June 13 the barley in containers 6, 7, and 8, and the potatoes in containers 3, 4, and 5 were examined. The barley had developed quite evenly with that grown outside of the containers and was in the blossoming stage, although a few of the older heads had begun to fill. The plants had tillered well. The crop had an average height of about 2.8 feet, except that those plants in container 7, which had been slightly damaged by frost, were only about 2.5 feet tall (maximum 3.2 feet, plate 13 A). The potatoes were 1.7 to 2 feet tall, had developed normally as compared with those in an adjoining field, and were just beginning to blossom. The position of the wax seals inclosing the fertilized soil layers and the extent of the root development is shown in figure 42. Here again the effect of the fertilized soil upon limiting root penetration, as well as increasing the degree of branching, is patent. That the wax seal offered no obstacle to root penetration is clearly shown in plate 9 C, where a portion of the seal taken at a depth of 2 feet from container 8 is shown. The high degree of root development in this fertilized layer (depth 2 to 2.5 feet) is also shown in the same plate. Glass funnels 3 inches in diameter and partly filled with coarse sand were placed inverted in the several containers at depths indicated in table 40. These were connected with large glass tubes which extended 2 inches above the soil-surface, where they were kept corked. These furnished a means of adding water to the soil. The loss of water and nitrates, together with the crop development, is given in table 40.

A survey of table 40 shows that the amount of water absorbed by the potatoes, while not so great as in the case of barley, was quite uniform in the several containers and corresponds well with root depth and distribution. The nitrates removed at the different levels, while quite marked in amount, were also less than that used by barley. Water-losses from the containers with barley were greatest from the first foot (7 to 13 per cent), but large quantities had also been removed from the second-foot layers (2 to 7 per cent),

TABLE 40.—*Loss of water and nitrates, April 1 to June 13.*

Container and crop development.	Depth.	Water-content.			Nitrate, parts per million.			
		Apr. 1.	June 13.	Loss.	Apr. 1.	Gain by nitrification.	June 13.	Loss.
	feet.	*p. ct.*	*p. ct.*	*p. ct.*				
No. 3. Potatoes, 3 stalks, beginning to blossom; 10 tubers 3 to 10 mm. in diameter; roots unevenly distributed to a depth of 1.5 ft., none deeper, as abundant in fertilized layer as elsewhere and more profusely branched.	0 to 0.5	22.1	18.0	4.1	.....	......	.....	.....
	0.5 to 1	21.9	18.5	3.4	.....	......	.....	.....
	1 to 1.5	22.5	21.3	1.2	363.5	185.0	405.0	143.5
	1.5 to 2	22.8	22.8	0.0	.....	......	.....	.....
	2 to 2.5	25.3	24.6	0.7	.....	......	.....	.....
No. 4. Potatoes, 3 stalks, more leaves than in No. 3; eight tubers 1 to 30 mm. in diameter; roots fairly abundant to 1.5 ft., less abundant to 2 ft., below which none penetrated.	0 to 0.5	25.9	20.8	5.1	.....	......	.....	.....
	0.5 to 1	25.3	20.9	[1]4.4	.....	......	.....	.....
	1 to 1.5	22.0	20.2	1.8	.....	......	.....	.....
	1.5 to 2	21.8	20.6	1.2	361.7	155.4	447.0	70.1
	2 to 2.5	23.8	22.9	0.9	.....	......	.....	.....
No. 5. Potatoes, 2 stalks, beginning to blossom; 8 tubers 2 to 20 mm. in diameter; roots fairly abundant to 1.5 ft., some reaching a depth of 2 ft.	0 to 0.5	25.2	21.0	[1]4.2	.....	......	.....	.....
	0.5 to 1	25.4	21.6	3.8	.....	......	.....	.....
	1 to 1.5	23.7	20.5	[1]3.2	.....	......	.....	.....
	1.5 to 2	24.8	24.2	0.6	.....	......	.....	.....
	2 to 2.5	23.5	23.7	+0.2	.....	......	.....	.....
No. 6. Barley, 67 stalks with heads, many small stalks without heads; roots abundant to 1.5 ft., fairly abundant to 2 ft., below which they were sparse.	0 to 0.5	29.0	15.7	13.3	.....	......	.....	.....
	0.5 to 1	25.6	13.5	[2]12.1	.....	......	.....	.....
	1 to 1.5	24.7	19.0	5.7	375.4	185.0	274.0	286.4
	1.5 to 2	24.4	20.4	4.0	.....	......	.....	.....
	2 to 2.5	23.6	22.6	1.0	.....	......	.....	.....
No. 7. Barley, 60 stalks with heads, smaller stalks without heads, not so well developed as in 6 and 8; roots very abundant to 2 ft., below which none was found.	0 to 0.5	27.8	21.3	6.5	.....	......	.....	.....
	0.5 to 1	26.7	19.1	[2]7.6	.....	......	.....	.....
	1 to 1.5	24.6	19.6	5.0	.....	......	.....	.....
	1.5 to 2	23.2	20.9	2.3	371.0	155.4	391.0	135.4
	2 to 2.5	21.8	22.6	+0.8	.....	......	.....	.....
No. 8. Barley, 75 stalks with heads, similar to No. 6; roots abundant and evenly distributed to 2.5 ft., only more branched in 2 to 2.5 ft. layer.	0 to 0.5	28.4	14.4	14.0	.....	......	.....	.....
	0.5 to 1	23.8	15.1	[3]8.7	.....	......	.....	.....
	1 to 1.5	24.0	16.6	7.4	.....	......	.....	.....
	1.5 to 2	24.8	18.2	[3]6.6	.....	......	.....	.....
	2 to 2.5	22.4	20.7	1.7	408.7	103.6	344.0	168.3

[1] Two liters of water were added to the soil at this depth during the growth of the plants.
[2] Seven liters of water added.
[3] Four liters of water added.

while in some of the containers, especially No. 8, where the fertilized layer was deep, the roots had penetrated well below 2 feet and had carried on considerable absorption. Barley roots were active not only in absorbing water, but they were also removing the nutrient in considerable amounts. The loss at 2 to 2.5 feet depth (168.3 parts per million) is especially striking.

The barley was ripe on July 1, the heads being well filled. However, it was allowed to stand until July 9, when it was finally examined, along with

the potatoes, the tops of which were ripening rapidly. At this time the soil in container 9, which bore no crop, was also examined. The results obtained from this examination are given in table 41.

TABLE 41.—*Loss of water and nitrates, April 1 to July 9.*

Container and crop development.	Depth.	Water-content.			Nitrates, parts per million.			
		Apr. 1.	July 9.	Loss.	Apr. 1.	Gain by nitrification.	July 9.	Loss.
	feet.	*p. ct.*	*p. ct.*	*p. ct.*				
No. 9. Control. No plants.	0 to 0.5	24.7	22.9	1.8	0.0	210.0	210.0	+210.0
	0.5 to 1	24.5	23.8	0.7	0.0	251.0	251.0	+251.0
	1 to 1.5	25.0	24.8	0.2	11.4	252.6	264.0	+252.6
	1.5 to 2	22.9	22.5	0.4	11.4	204.6	216.0	+204.6
	2 to 2.5	24.1	23.2	0.9	51.3	140.7	192.0	+140.7
No. 10. Potatoes, 3 stalks 1.5 to 2 ft. tall; 4 tubers 1 to 2 in. in diameter, several smaller ones. Roots abundant to 2 ft., fairly abundant to 2.5 ft.	0 to 0.5	28.5	23.8	4.7	.....	.....	.....	.....
	0.5 to 1	24.3	22.3	[1]2.0	.....	.....	.....	.....
	1 to 1.5	24.4	20.3	4.1	.....	.....	.....	.....
	1.5 to 2	23.1	20.8	2.3	364.4	204.6	341.0	228.0
	2 to 2.5	23.1	21.0	2.1	358.7	140.7	423.0	76.4
No. 11. Potatoes, 2 stalks 2 ft. tall, 2, 1.7 ft.; 6 tubers about 1.5 in. in diameter, several smaller ones; roots abundant to 2.5 ft., only a few penetrated deeper.	0 to 0.5	27.8	19.7	8.1	.....	.....	.....	.....
	0.5 to 1	23.4	21.5	[1]1.9	.....	.....	.....	.....
	1 to 1.5	24.6	21.3	3.3	.....	.....	.....	.....
	1.5 to 2	23.3	20.4	2.9	.....	.....	.....	.....
	2 to 2.5	22.7	21.7	1.0	358.3	140.7	334.0	165.0
	2.5 to 3	24.5	23.9	0.6	.....	.....	.....	.....
	3 to 3.5	19.3	20.4	+1.1	.....	.....	.....	.....
No. 12. Barley, 154 stalks with 101 large well-filled heads, ave. ht. 2.5 ft.; roots abundant to 2.5 ft., beyond which few penetrated.	0 to 0.5	24.8	23.5	[2]1.3	.....	.....	.....	.....
	0.5 to 1	24.6	14.8	9.8	.....	.....	.....	.....
	1 to 1.5	25.9	19.8	[3]6.1	.....	.....	.....	.....
	1.5 to 2	24.8	17.4	7.4	.....	.....	.....	.....
	2 to 2.5	27.4	21.1	6.3	412.2	140.7	413.0	139.9
	2.5 to 3	23.6	24.1	+0.5	.....	.....	.....	.....
	3 to 3.5	22.7	21.8	0.9	.....	.....	.....	.....
No. 13. Barley, 135 stalks with 112 large, well-filled heads, av. ht. 2.5 ft.; roots abundant to 2.5 ft., fairly abundant to 3 ft., beyond which a few penetrated 3 to 5 inches.	0 to 0.5	27.3	19.0	8.3	.....	.....	.....	.....
	0.5 to 1	26.3	14.3	[3]12.0	.....	.....	.....	.....
	1 to 1.5	24.2	17.2	7.0	.....	.....	.....	.....
	1.5 to 2	25.2	17.9	[3]7.3	.....	.....	.....	.....
	2 to 2.5	25.4	22.8	2.6	.....	.....	.....	.....
	2.5 to 3	24.7	23.0	1.7	415.3	140.7	370.0	186.0
	3 to 3.5	24.1	24.9	+0.8	.....	.....	.....	.....
	3 to 3.5	23.0	23.6	+0.6	.....	.....	.....	.....

[1] Eight liters of water were added to the soil at this depth during the growth of the plants.
[2] Five liters of water added.
[3] Six liters of water added.

In table 41, the control container shows marked gains by nitrification at all depths. The water-losses from this container, except for evaporation through the slit in the roof from the surface 6 inches, fall well within the experimental error of sampling. The potatoes had reduced the water-content to the depth of root penetration, while the absorption of nitrates was also in close agreement with root distribution. So few roots penetrated beyond 2.5 feet that nitrate-losses at this depth were not determined.

The water used by the barley in container 12 was very similar in amount at all depths to which the roots were abundant (2.5 feet); that in container 13 was less below 2 feet. A comparison of these losses with those from plants unearthed on June 13 (table 40) shows clearly the great activity of the deeper and younger roots during the interval between blossoming and maturity. The loss of nitrates at 2 to 2.5 feet was less from container 12 than from container 8, which was excavated on June 13. However, the absorption at 2.5 to 3 feet (186 parts per million) shows conclusively the activity of the younger roots.

Iowa Silver Mine corn was planted on May 4. The cylindrical container, which was 3 feet wide and 5 feet deep, was sunk into the soil in the center of an area which was planted to corn (plate 14 A). The fourth and fifth foot were filled with soil from the 4-foot level from the lower crop plats. This had been impregnated with the usual amount of sodium nitrate, wax seals being placed at depths of 3 and 4 feet. The third foot was filled with impregnated soil from the corresponding level from the lower crop plats and separated by a wax seal from the first and second foot of surface soil, taken from the crop plats where the experiment was conducted. Only a part of the surface was covered by the seal, a circular area about 10 inches in diameter in the center of the container being covered by sand only. Two 5-inch funnels, inverted and partially filled with sand and connected with large glass tubes which passed through the wooden roof, afforded means of watering the first and second foot of soil. Three stalks of corn were grown in the hill in the center of the container. The crop developed rapidly, reaching a maximum height of 11.3 feet when the pollen was shedding on July 10 (plate 14 B).

Growth conditions (discussed on p. 88; *cf.* also fig. 41) remained favorable during July and the first half of August. Warm weather with abundant rains caused the crop to thrive, the corn in the container being furnished the necessary water, from time to time, through the funnels. In this manner 50 liters of water were added to both the first and second foot of soil, while on July 25 the roof and surface seal were removed and 20 liters of water were poured slowly on the soil. This was repeated on August 2, when 12 liters were added. After each watering a mulch of straw covered with sand was put on the surface before the wooden roof was replaced.

The container was excavated and the contents examined on August 15. At this time the three large stalks were 10.5 to 11.5 feet tall, about 1.2 inches in diameter at a height of 2 feet, and each had a large ear about 10 inches long at a height of 6 feet. The lower leaves were drying and the kernels were well filled and beginning to dent.

The first 2 feet of soil (from which no samples were taken) were very well occupied by roots and were quite dry, the first foot breaking up into lumps. The roots had penetrated the seal at 2 feet and branched so abundantly in the fertilized soil below that they were even more abundant than in the surface soil. Every cubic centimeter of soil seemed well filled with roots. In the fourth foot the roots were very abundant, but somewhat fewer than in the third-foot layer. Below 4 feet the roots were sparse; none extended deeper than 4.5 feet. The cause for the shorter root system (the corn roots outside reached depths of over 5 feet) was undoubtedly due to the rich subsoil. The long, white, unbranched root-ends indicated that growth was not yet

complete. The losses of water and nitrates in the sealed layers are given in table 42.

TABLE 42.—*Loss of water and nitrates, May 4 to August 15.*

Depth.	Water-content.			Nitrates, parts per million.			
	May 4.	Aug. 15.	Loss.	May 4.	Gain by nitrification.	Aug. 15.	Loss.
feet.	*p. ct.*	*p. ct.*	*p. ct.*				
2 to 3.......	22.1	17.8	4.3	407.8	144.2	349.0	203.0
3 to 4.......	21.9	18.4	3.5	395.4	133.9	389.0	140.3
4 to 5.......	25.8	23.2	2.6	407.1	133.9	423.0	118.0

Absorption of water at the various depths is directly correlated with the abundance of roots and the time the roots were present and active at the several levels. The nitrate losses, while decreasing with depth as one would anticipate, are sufficiently marked to show clearly that in studies of soil fertility more than the surface soil must be taken into account.

The native grasses were planted as blocks of sod approximately 8 inches long, 5 inches wide, and 6 inches deep. These were secured from the field on May 4, when the new growth, which was cut back, was about 3 inches high. The containers in which they were placed were filled with lowland soil to which nitrates had been added at depths of 1 to 2.5 feet, seals being inserted in the fertilized soil at depths of 1 and 2 feet respectively. The surface foot of soil consisted of the rich loam taken from the crop plats. No seal or sand was used on the surface. Openings the size and shape of the surface of the sods were cut in the roofs to permit the growth of the grasses from the entire blocks. The first foot of soil was kept well watered and the grasses grew very rapidly. By July 20 flowering stalks had begun to appear, and by August 15, when they were examined finally, they had made an excellent growth. *Agropyrum glaucum* was 2.5 feet tall, but had not headed out, while *Andropogon furcatus* had flowering stalks 4 to 6.7 feet tall, some of which were beginning to blossom (plate 13 B). Unfortunately, *Andropogon scoparius*, which had also made an excellent early growth, became waterlogged and could not be used.

TABLE 43.—*Loss of water and nitrates, May 4 to August 15.*

Plant.	Depth.	Water-content.			Nitrates, parts per million.			
		May 4.	Aug. 15.	Loss.	May 4.	Gain by nitrification.	Aug. 15.	Loss.
	feet.	*p. ct.*	*p. ct.*	*p. ct.*				
Agropyrum glaucum.....	1 to 2	24.0	18.2	5.8	371.9	236.9	485.0	123.8
	2 to 2.5	24.7	21.3	3.4	415.3	144.2	337.0	222.5
Andropogon furcatus.....	1 to 2	23.7	15.0	8.7	372.3	236.9	231.0	378.2
	2 to 2.5	28.7	25.9	2.8	427.1	144.2	246.0	325.3

Wheat-grass roots were very abundant to the bottom of the container (depth 2.5 feet) where they were slightly massed. They penetrated thoroughly all portions of the soil, but were especially well branched in the fertilized layers below the first foot. The roots of the big bluestem were also splendidly developed and especially abundant in the second foot. They had not filled the third foot of soil so completely as the wheat-grass. Water and nitrate absorption by the grasses is given in table 43.

The amount of water used by the grasses is rather remarkable when the brief period of growth is taken into consideration. However, studies of the life-history of grasses (Clements and Weaver, 1921) impress one with the rapidity of root development. The removal of nitrates is also very marked, exceeding considerably in amount that removed by any crop plants used in these experiments.

Summary.

The great depth to which the roots of both native and crop plants penetrate has led the writers to perform a series of experiments to determine the amount of water and nutrients absorbed from the deeper soils. In these experiments containers 1.5 to 3 feet in diameter and 2.5 to 5 feet deep were employed. They were placed in trenches, which were then refilled with soil and crops planted around the containers in such a manner that the experimental crops in the containers were grown under field conditions. The containers were filled with well-mixed soil of known water-content and physical and chemical composition, to which, at certain levels, $NaNO_3$ had been added at the rate of 400 parts per million. The containers were filled in such a manner that the well-compacted soil at any level occupied the same relative position as regards depth that it had occupied before removal from the field. The fertilized layers, and in some cases every 6-inch layer, were separated from the rest of the soil by wax seals which prevented the movement of water or solutes, but through which the roots readily penetrated. To prevent water intake each container was furnished with an appropriate wooden roof. The experiments extended over a period of 2 years, during which time the following crops were grown: oats, barley, potatoes, corn, and two native grasses (*Agropyrum glaucum* and *Andropogon furcatus*). In order to study the activities of the roots at various stages in their development, enough containers were used (about 50 in all) so that some could be examined at each of the several periods of growth of the crops.

Preliminary experiments with oats showed that this crop absorbed water at all depths to 2.5 feet, even before blossoming. The amount of water absorbed by barley from the deeper soils (to 3.5 feet) is in direct relation to the growth of the root system into these deeper layers. The total amounts absorbed to depths of 2.5 feet were in general practically the same from the several 6-inch levels. Corn is an extravagant user of water, absorbing large quantities from the third and fourth foot of soil and smaller amounts from the fifth foot. Potatoes absorbed water to depths of 2.5 feet (approximately the limit of root extent), while the native grasses, grown from transplanted sods, showed marked absorption to a similar depth.

Barley at the age of 54 days had removed 168 and 145 parts per million of nitrates from the 1 to 1.5 and 1.5 to 2 foot soil-levels respectively. When in

blossom (19 days later) it had removed 286 and 135 parts per million of the nitrates from similar levels, and 168 parts per million from the 2 to 2.5 foot level. At maturity it had removed 186 parts per million from the 2.5 to 3 foot level. Potatoes used the nitrates in smaller amounts. When beginning to blossom (74 days old) they had removed 143 and 70 parts per million of nitrates from the 1 to 1.5 and 1.5 to 2 foot layers respectively, and when beginning to ripen (100 days old) 228 parts per million had been removed at a depth of 1.5 to 2 feet, and 76 to 165 parts per million at the 2 to 2.5 foot level. *Agropyrum* and *Andropogon* used nitrates from the second and third foot in large amounts (124 to 378 part per million), while corn removed 203, 140, and 118 parts per million at depths of 3, 4, and 5 feet respectively.

Under greenhouse conditions both tops and roots of barley developed so poorly that little value is attached to such experiments when applied to field conditions. However, the absorption of water and nitrates to 2.5 feet (the maximum depth of root extent) correlated nicely with root position and development.

In every case where roots came in contact with a fertilized layer they not only developed much more abundantly and branched more profusely, but such a layer apparently retarded normal penetration into the soil below. Thus it seems that the depth at which the fertilizer is placed in field practice would considerably affect root position and development. Fertilizing the surface layers of soil in regions where these have very little or no available water during periods of drought would appear to be distinctly detrimental to normal crop production. Finally, since the roots of crop plants are found to penetrate just as deep, or even deeper, under field conditions as in the containers used in these experiments, and since their development in every respect has been found to be identical, we must conclude that the deeper soils are not only suited to plant-life, but that they play an exceedingly important part in the life of the plant and deserve careful consideration in a study of crop production.

BIBLIOGRAPHY.

Alten, H. von. 1909. Wurzelstudien. Bot. Zeit. 67 : 175.

Alway, F. J. 1913. Studies on the relation of the non-available water of the soil to the hygroscopic coefficient. Nebr. Agr. Exp. St. Res. Bull. 3.

——— and Guy R. McDole. 1917. Relation of the water-retaining capacity of a soil to its hygroscopic coefficient. Jour. Agr. Res. 9 : 27.

——— ——— 1917. Relation of movement of water in a soil to its hygroscopicity and initial moistness. Jour. Agr. Res. 10 : 391.

——— and J. C. Russel. 1916. Use of the moisture equivalent for the indirect determination of the hygroscopic coefficient. Jour. Agr. Res. 6 : 833.

——— *et al.* 1919. Relation of minimum moisture content of subsoil of prairies to hygroscopic coefficient. Bot. Gaz. 67 : 185.

Beckwith, M. H. 1885. Report of the assistant horticulturist. N. Y. Agr. Exp. Sta. Rep. 4 : 261.

Bergman, H. F. 1920. The relation of aeration to the growth and activity of roots and its influence on the ecesis of plants in swamps. Ann. Bot. 34 : 13.

Briggs, L. J., and J. O. Belz. 1910. Dry farming in relation to rainfall and evaporation. U. S. Dept. Agr., Bur. Pl. Ind. Bull. 188.

——— and H. L. Shantz. 1912. The wilting coefficient for different plants and its indirect determination. U. S. Dept. Agr., Bur. Pl. Ind. Bull. 230.

Burr, W. W. 1910. Storing moisture in the soil. Nebr. Agr. Exp. St. Bull. 114.

Clements, F. E. 1916. Plant succession. Carnegie Inst. Wash. Pub. 242.

——— 1920. Plant indicators. Carnegie Inst. Wash. Pub. 290.

——— and J. E. Weaver. 1921. Transplant quadrats and areas. Carnegie Inst. Wash. Year Book 20 : 401.

Cannon, W. A. 1911. The root habits of desert plants. Carnegie Inst. Wash. Pub. 131.

——— 1915. On the relation of root growth and development to the temperature and aeration of the soil. Am. Jour. Bot. 2 : 211.

——— 1918. The evaluation of the soil temperature factor in root growth. Plant World 21 : 64.

——— and E. E. Free. 1917. The ecological significance of soil aeration. Science 45 : 178.

——— ——— 1920. Root adaptation to deficient soil aeration. Carnegie Inst. Wash. Year Book 19 : 62.

Chilcott, E. C., and John S. Cole. 1917. Growing winter wheat on the Great Plains. U. S. Dept. Agr., Farmers' Bull. 895.

Garner, W. W., and H. A. Allard. 1920. Effect of the relative length of day and night and other factors of the environment on growth and reproduction in plants. Jour. Agr. Res. 18 : 553.

Goff, E. S. 1887. Report of the horticulturist. N. Y. State Exp. Agr. Sta., 6th Ann. Rep., p. 90.

——— 1897. Study of roots of certain perennial plants. Wis. Agr. Exp. Sta. Rep. 14 : 286.

Hays, W. M. 1889. Corn, its habits of root growth, methods of planting and cultivation. Minn. Agr. Exp. Sta. Bull. 5 : 5.

Hickman, J. C. 1887. Root development of corn. Director's Rep., Penn. State Col. 2 : 90.

Hole, R. S. 1918. Recent investigations on soil aeration. Indian Forester 1918 : 202.

Howard, A. 1916. Soil aeration in agriculture. Pusa Agr. Res. Inst. Bull. 61.

——— 1918. Recent investigations on soil aeration. Indian Forester 1918 : 187.

——— and G. L. C. Howard. 1915. Soil ventilation. Pusa Agr. Res. Inst. Bull. 52.

——— ——— 1917. The economic significance of the root development of agricultural crops. Agr. Jour. India, Indian Sci. Congr. Number.

Hunter, C. 1912. Some observations on the effect of soil aeration on plant growth. Proc. Phil. Soc. Univ. Durham 4 : 183.

Jones, L. R. 1917. Soil temperatures as a factor in phytopathology. Plant World 20 : 229.

Kiesselbach, T. A. 1916. Transpiration as a factor in crop production. Nebr. Agr. Exp. Sta. Res. Bull. 6.

——— 1918. Studies concerning the elimination of experimental error in comparative crop tests. Nebr. Agr. Exp. Sta. Res. Bull. 13.

King, F. H. 1892. Natural distribution of roots in field soils. Wis. Agr. Exp. Sta. Rep. 1892 : 112; also 1893 : 160.

Lehenbauer, P. A. 1914. Growth of maize seedlings in relation to temperature. Phys. Res. 1 : 247.

Miller, Edwin C. 1916. The root systems of agricultural plants. Jour. Am. Soc. Agron. 8 : 129.

——— 1916. Comparative study of the root systems and leaf areas of corn and the sorghums. Jour. Agr. Res. 6 : 311.

Nobbe, F. 1862. Ueber die feinere Verastelung der Pflanzenwurzeln. Landw. Versuchst. 4 : 212.

Osvald, H. 1919. Untersuchungen über die Einwirkung des Grundwasserstands auf die Bewurzelung von Wiesenpflanzen auf Moorboden. Fühling's Landw. Zeit. 68 : 321, 370.

Pool, R. J., J. E. Weaver, and F. C. Jean. 1918. Further studies in the ecotone between prairie and woodland. Bot. Surv. Nebr., n. s. 2 : 1.

Pulling, Howard E. 1918. Root habit and plant distribution in the far north. Plant World 21 : 223.

Robbins, W. W. 1917. The botany of crop plants.

Rotmistrov, V. 1909. Root-system of cultivated plants of one year's growth.

——— 1914. Nature of drought. Relation of root systems to soil and drought. Review in Exp. Sta. Rec. 31 : 514.

Russell, Edward J. 1917. Soil conditions and plant growth.

Shantz, H. L. 1911. Natural vegetation as an indicator of the capabilities of land for crop production in the Great Plains area. U. S. Dept. Agr., Bur. Pl. Ind. Bull. 201.

Shepperd, J. B. 1905. Root systems of field crops. N. Dak. Agr. Exp. Sta. Bull. 64.

Sturtevant, E. L. 1882. In Rep. Conn. Bd. Agr., 70.

Tacke, B. 1920. Untersuchung der Wurzeln und Kalk Inhalt des Bodens. Fühling's Landw. Ztg. 69 : 58.

Ten Eyck, A. M. 1899. Roots of plants. N. Dak. Agr. Exp. Sta. Bull. 36.

——— 1900. A study of the root systems of cultivated plants grown as farm crops. N. Dak. Agr. Exp. Sta. Bull. 43.

——— 1904. The roots of plants. Kans. Agr. Exp. Sta. Bull. 127.

Truog, Emil. 1918. Soil acidity: I. Its relation to the growth of plants. Soil Science 5 : 169.

Vorob'ev, S. I. 1916. On the study of the root systems of cereals and forage plants. Selsk. Khoz. Liesov. 251 : 477.

Weaver, J. E. 1915. A study of the root-systems of prairie plants of southeastern Washington. Plant World 18 : 227.

——— 1917. A study of the vegetation of southeastern Washington and adjacent Idaho. Univ. Nebr. Studies 17 : 1.

——— 1919. The ecological relations of roots. Carnegie Inst. Wash. Pub. 286.

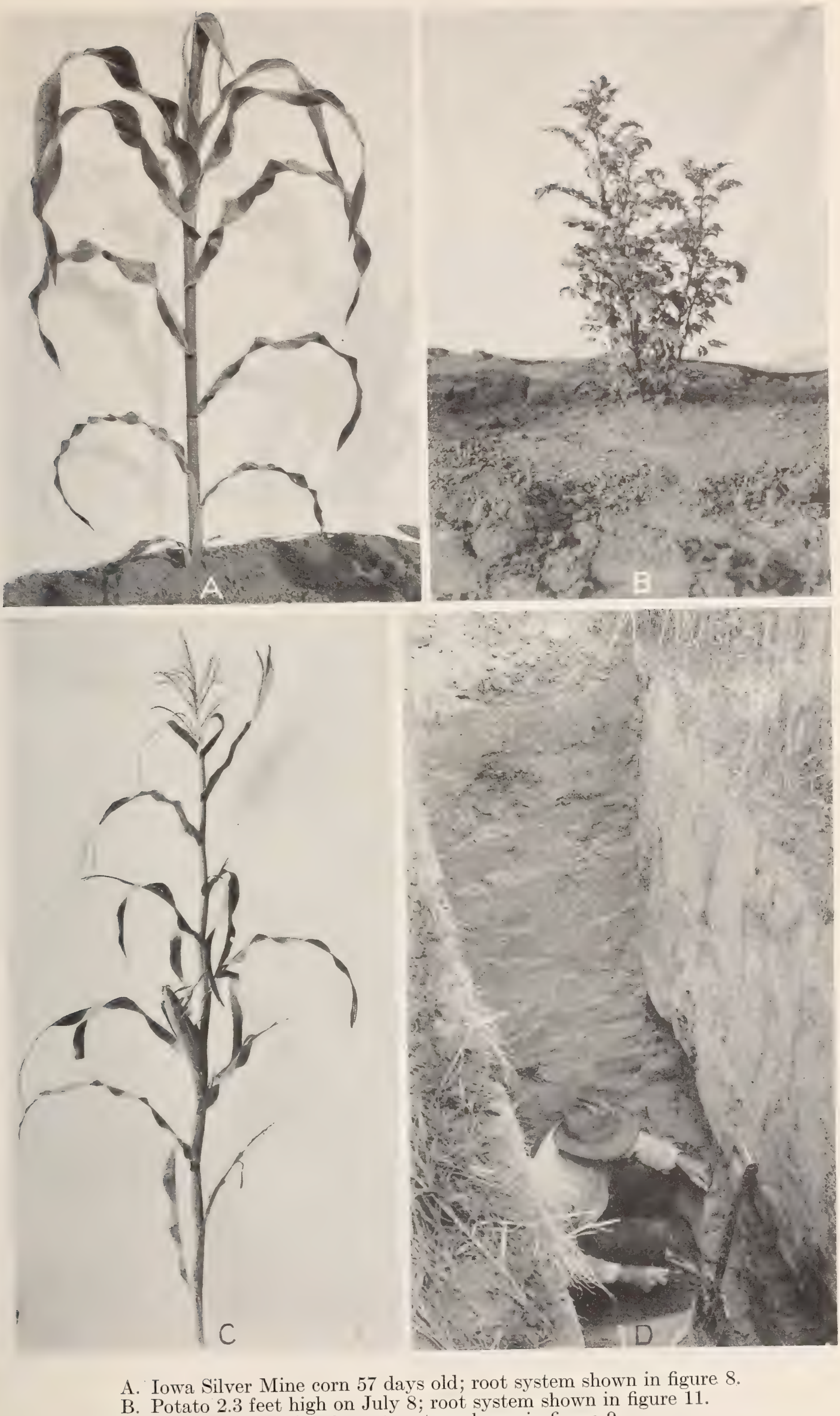
——— 1920. Root development in the grassland formation. Carnegie Inst. Wash. Pub. 292.

——— 1921. Plant production quadrats. Carnegie Inst. Wash. Year Book. 20 : 400.

——— and John W. Crist. 1922. Relation of hardpan to root penetration in the Great Plains. In press.

Whiting, A. L., T. E. Richards, and W. R. Schoonover. Nitrate determination in soils. Jour. Ind. Eng. Chem. 12 : 982.

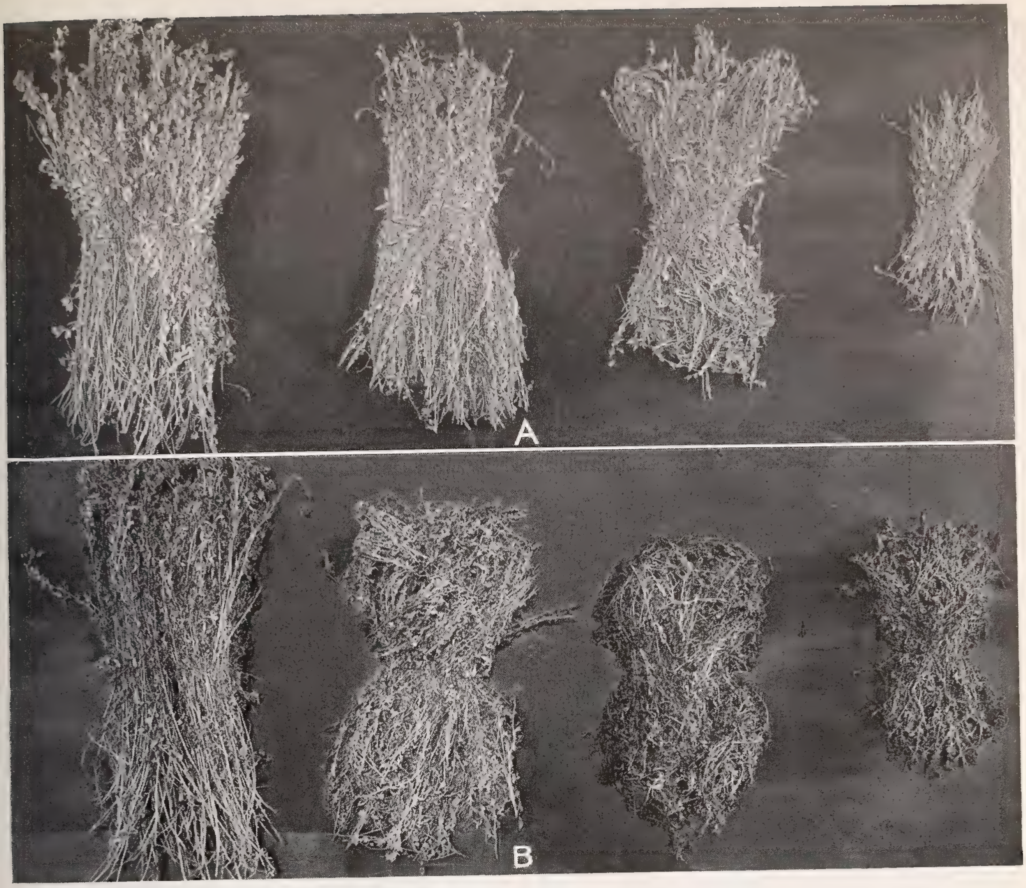
PLATE 1



A. Iowa Silver Mine corn 57 days old; root system shown in figure 8.
B. Potato 2.3 feet high on July 8; root system shown in figure 11.
C. Corn on September 2; root system shown in figure 9.
D. Trench used in examining the roots of cereals.

A. Marquis Spring wheat at Burlington, 1920.
B. Marquis Spring wheat from a square meter at Burlington (left), Phillipsburg, and Lincoln.

A. White Kherson oats from a square meter at Burlington (left), Phillipsburg, and Lincoln.
B. Manchuria barley from a square meter at Burlington (left), Phillipsburg, and Lincoln.



A. Four hundred plants of alfalfa from lower crop plats (left) and upper crop plats at Lincoln; and from Phillipsburg and Burlington, respectively.
B. Three hundred plants of sweet clover from lower crop plats (left) and upper crop plats at Lincoln; and from Phillipsburg and Burlington, respectively.

A

B

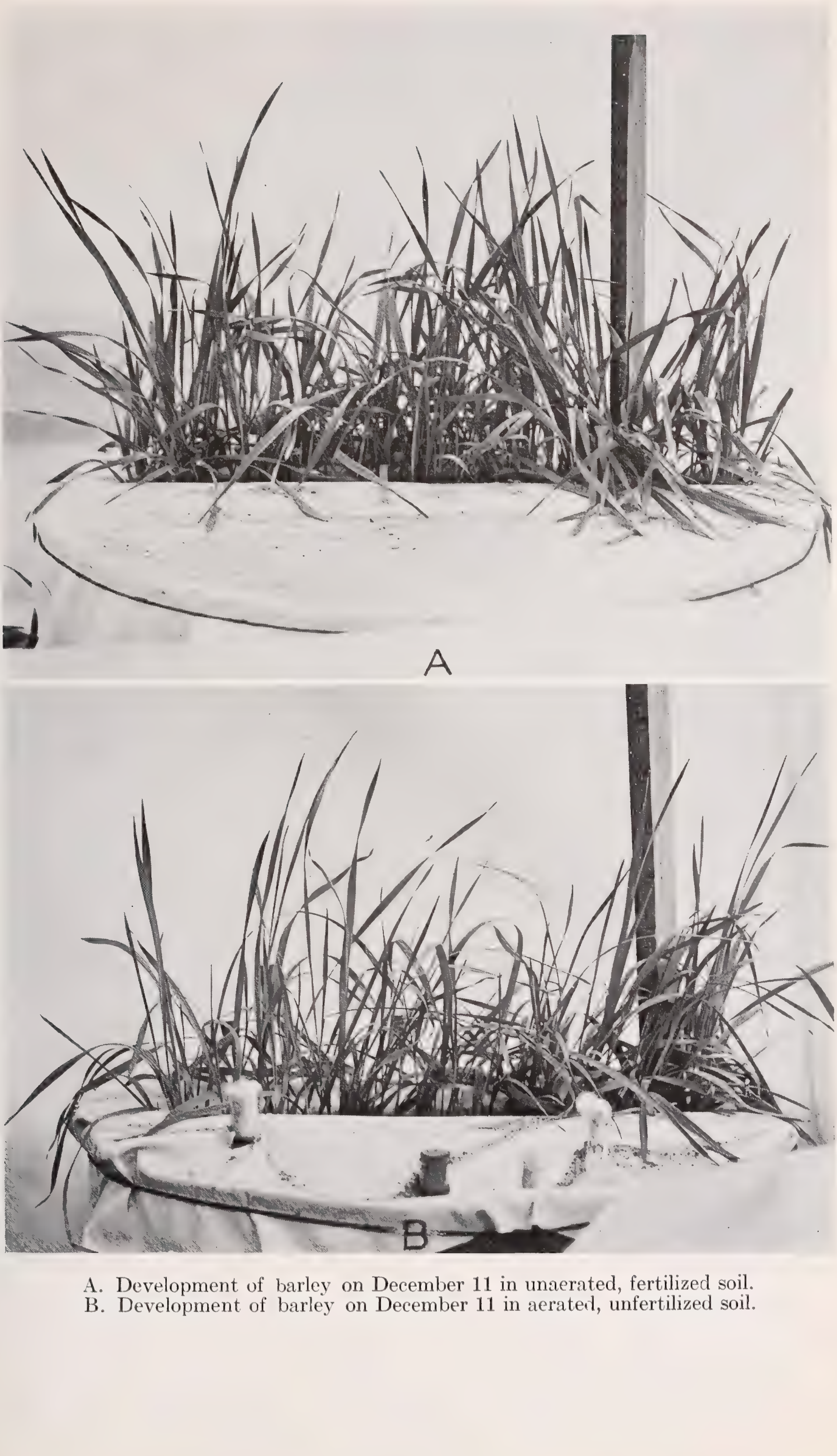
A. Wheat from Lincoln (left), Phillipsburg, and Burlington, May 18–21.
B. Barley from Lincoln (left), Phillipsburg, and Burlington, May 18–21.

A. Oats at Lincoln, May 18.
B. Oats at Phillipsburg, May 19.
C. Oats at Burlington, May 20.

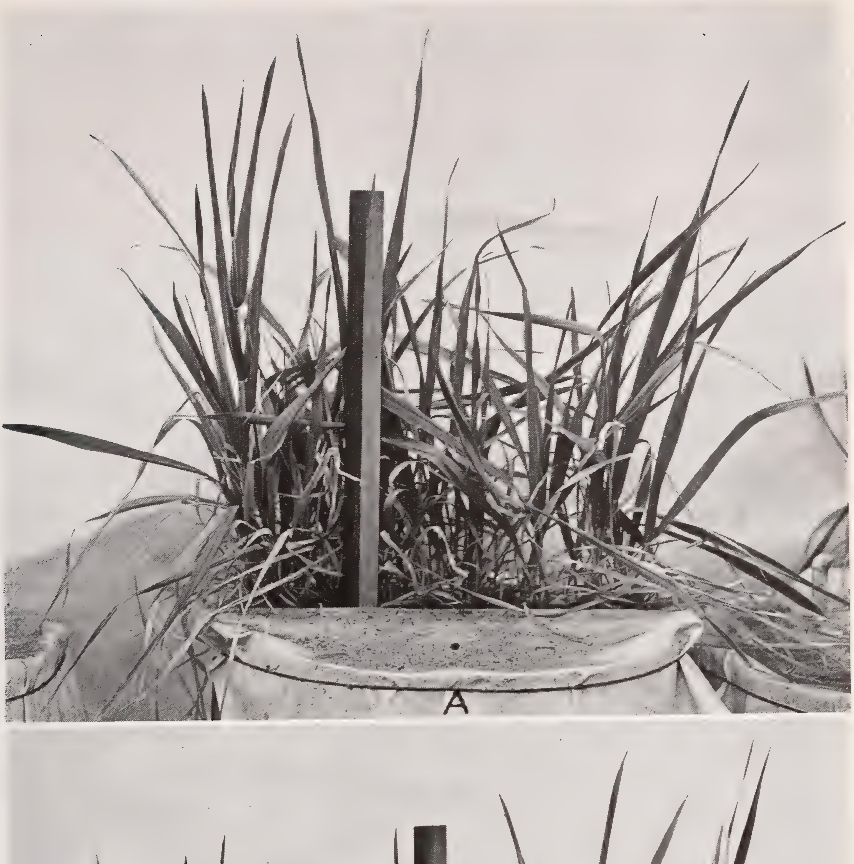
A. Wheat from Lincoln (left), Phillipsburg, and Burlington, June 10.
B. Barley from Lincoln (left), Phillipsburg, and Burlington, June 10.

A. Oats at Lincoln, June 10.
B. Oats at Phillipsburg, June 10.
C. Oats at Burlington, June 10.

A. Barley grown in container with wax seals at 6-inch intervals.
B. Same with upper portion of container removed.
C. Wax seal at depth of 2 feet (left) showing the penetration of the seal by roots and their abundance under field conditions. Fertilized soil at 2.5 feet depth filled with copiously branched roots.
D. Arrangement of containers in greenhouse experiment, 1920–21.



A. Development of barley on December 11 in unaerated, fertilized soil.
B. Development of barley on December 11 in aerated, unfertilized soil.



A. Development of crop on March 12 in fertilized soil.
B. In unfertilized soil.

A. General view of one row of containers, May 17.
B. Detailed view of barley and potatoes, May 17.

A. Potatoes and barley on June 13.
B. Native grasses on August 15, at the time of examination.

A. Development of corn, June 5.
B. Development of corn, July 10.